PERKIN-ELMER

OPTICAL GROUP NORWALK, CONNECTICUT

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FINAL REPORT
QUIET LASER PROGRAM

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SECTION I

INTRODUCTION

The Quiet Laser Program was a study of the methods of achieving outstanding short-term frequency stability in gas lasers. The program consisted of two major tasks.

The first task was a study of the factors affecting the short-term frequency stability of open-loop lasers. This phase of the program resulted in the design and building of four open-loop single mode diffraction limited lasers. Two of these lasers were simply thermally stabilized and delivered to Marshall Space Flight Center in June, 1966. They achieved a stability of a few parts in 10^9 per hour. The remaining lasers were used for the work in the second part of the program.

The second task completed during the Quiet Laser Program was to slave the frequencies of two open-loop lasers to the resonant frequencies of two independent passive reference cavities. The resulting drift rate was substantially better than that of the open-loop lasers alone. The program ended with the delivery of two complete stabilized laser systems.

The use of a passive resonant cavity to improve the frequency stability of a laser is analogous to using an external cavity to control the frequency of a microwave oscillator. Because the passive cavity serves only as a frequency reference, it can be designed for the single purpose of providing intrinsic stability. Unlike using the laser itself for a frequency reference, using an external reference does not compromise the stability inherently available from the best materials and structures.

The stability of a laser can be characterized by two parameters: its linewidth and its drift rate. When the beat frequency between two identical lasers is displayed on a panoramic spectrum analyzer, it is characterized by a width and a rate of motion across the screen. The width at half power of this beat signal is a measure of the linewidth of the lasers. The movement of the center of the beat signal is a measure of the drift rate of the lasers. The linewidth is expressed in Hz and the drift rate in Hz per hour.

The open-loop lasers developed during this program had a linewidth of approximately 15 kHz under average room noise conditions. The drift rate of these lasers when thermally stabilized was approximately 3 MHz per hour. The factors which determined this stability are discussed in Section II.

The drift rate of the closed-loop lasers was about 200 kHz per hour. The linewidth of 15 kHz remained unchanged. The factors which prevented reducing the linewidth by closed-loop feedback in these systems, and the factors which determined the system drift rate are discussed in Section III.

This program has contributed experience and some new techniques in the stabilization of gas lasers. Recommendations for future improved stable laser systems using these techniques are contained in Section V.

Section IV of this report describes the theory and operation of the closed-loop laser systems. These systems carry the designation "Externally Controlled Laser." An operation and service manual was shipped with the equipment and is partially reproduced as Appendix A.

SECTION II

FACTORS INFLUENCING THE STABILITY OF OPEN-LOOP GAS LASERS

The factors influencing the frequency stability of a gas laser may be divided into two groups. The first group are those factors which change the mechanical spacing between the laser resonator mirrors:

A. temperature drift of the resonator

B. spontaneous length changes of the resonator structure; including the spacer, piezoelectric mirror pusher, dielectric mirror coatings, etc.

C. resonant vibration of the structure

D. acoustical microphonic disturbances

The second group of frequency-disturbing factors are those which change the index of refraction (optical path) between the mirrors:

E. pressure fluctuations and chemical composition changes in the air space between the mirrors and plasma tube

F. convection air flow around the Brewster-angle windows

G. plasma noise

H. frequency pulling and mode interactions

A. TEMPERATURE EFFECTS

The effect of thermal drift in these lasers was measured under controlled conditions. Two open-loop lasers were optically heterodyned while thermally stabilized with a proportional temperature controller. The residual temperature drift of these thermostated lasers was approximately ±0.005°C per hour. Because of the coefficient of expansion of Invar, 5×10^{-7} per °C, one would expect a concomitant beat frequency drift rate of about 1.2 MHz per hour. The measured beat frequency showed a monotonic change with a rate of 3 MHz per hour. This larger than anticipated 3-MHz-per-hour drift rate of the open-loop lasers is thus only in part explained by temperature induced length changes in the resonator. This drift rate was later greatly reduced by the high-gain servo used in the closed-loop systems.

B. SPONTANEOUS LENGTH CHANGES

The other causes of long-term frequency instability are not yet known. They could plausibly be the result of material aging, or of instability of the piezoelectric mirror pusher.

Very little is known about the infinitesimal length changes in materials which could cause such very small drifts. Perkin-Elmer is now under contract to Advanced Research Projects Agency to make a study of the long-term dimensional stability of materials. This study may yield results useful in understanding the laser instabilities we now measure.

C. RESONANT VIBRATION OF THE STRUCTURE

The resonator used in these lasers incorporates two significant features. It is shown in Figure 1.

The first feature is its "negative dumbbell" shape which concentrates the mass and stiffness near the center. This configuration reduces

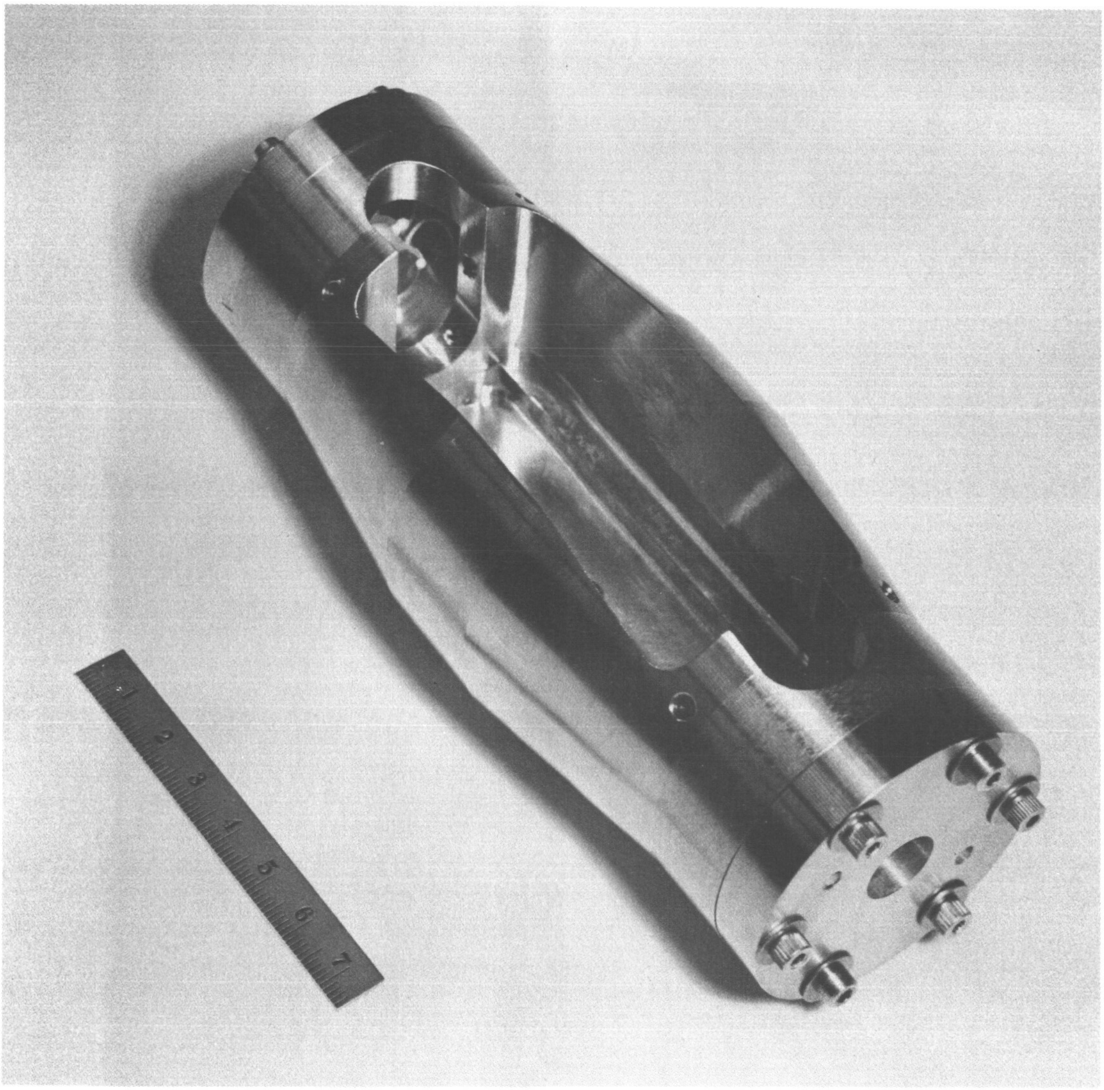


Figure 1. Laser Resonator

the transverse vibration of the mirrors. The longitudinal ("breathing") vibration resonant frequency is also raised as a result of this shape.

The second feature is the method of supporting the resonator. The fundamental longitudinal vibration mode of this resonator has a node at the midpoint. The entire resonator structure is supported at this node. This inhibits exciting of the "breathing" mode by disturbances in the support structure.

Some measure of the success of this design is evident from the fact that no resonant vibration of the structure could be discerned in the spectrum of the beat between the lasers.

D. ACOUSTICAL MICROPHONIC DISTURBANCES

Acoustically excited noise is the biggest source of FM disturbances in simple helium-neon (He-Ne) lasers of typical construction. Acoustically induced noise linewidths of 1 MHz to 10 MHz are common in many lasers under average room noise conditions. These sound disturbances can enter the laser either through the air, or through the structure, or both. The quiet laser design has an hermetically sealed thick-walled housing. This housing, in combination with the carefully designed resonator described above, resulted in a measured linewidth due to acoustical disturbances of 15 kHz. The detailed laser design is discussed in Section IV.

E. PRESSURE FLUCTUATIONS AND CHEMICAL COMPOSITION CHANGES

Lasers with Brewster-angle windows on the plasma tube usually have a small air space between the window and the mirror. Atmospheric pressure changes result in a change in index of refraction of the air in this gap.

This causes a change of the laser frequency. It is apparent that the fractional change in the laser frequency due to this effect is equal to the fractional change in the index of refraction of the air, multiplied by the fraction of the cavity which the air occupies.

$$\frac{\Delta\nu}{\nu} = f\,\frac{\Delta\Gamma}{\Gamma} = f\,\frac{\Delta L}{L} + f\,\frac{\Delta n}{n}$$

where

ν = laser frequency

Γ = optical path of the air space

L = geometrical path of the air space

n = index of refraction ($n_{air} = 1.0003$)

f = fraction of cavity spacing which is air space

for fixed L,

$$\frac{\Delta\nu}{\nu} = f\,\frac{\Delta n}{n} = f\,(n-1)\,\frac{\Delta P}{P}$$

where

P = air pressure

$$\boxed{\frac{\Delta\nu}{\nu} = f\,(3\text{x}10^{-4})\,\frac{\Delta P}{P}}$$

During a typical day the atmospheric pressure may vary by as much as 5 percent. If 10 percent of the cavity spacing is air space, the laser frequency shifts can be as much as 10^3 MHz. To eliminate this disturbance, the laser has been hermetically sealed in a rigid case.

Any changes in chemical composition or density of the air space due to outgassing or gas absorption in the hermetically sealed laser will also change the index of refraction in the air path between the mirrors. This effect has been observed in the reference cavities and is discussed in Section III.

F. CONVECTION FLOW AROUND BREWSTER WINDOWS

Because cooling of the plasma tube is partially by air convection, the air in the region about the plasma tube is in constant motion. This air current, if allowed to pass in the optical path of the resonator, will cause a low frequency noise. To eliminate this problem, the lasers have been designed with air current shields to keep the warm air flow away from the Brewster-angle windows as is shown in Figure 2.

G. PLASMA NOISE

RF pumping of He-Ne lasers results in discharges free from plasma oscillations. However, RF tubes have two limitations which precluded their use in this program.

First, "gas cleanup" (irreversible drop in gas pressure with time) severely limits the life and stability of RF excited tubes. The problem is related to the nonuniformity of pumping caused by local "hot spots" in the vicinity of the electrodes.

Second, is the limited freedom inherent in RF tube design. It is necessary to locate external electrodes in close proximity to the bore of the plasma tube.

DC pumped plasma tubes do not suffer from these limitations. By employing hot cathodes to minimize sputtering, they have a long stable life. DC excited plasma tubes offer considerably more flexibility in tube design than RF excited tubes do.

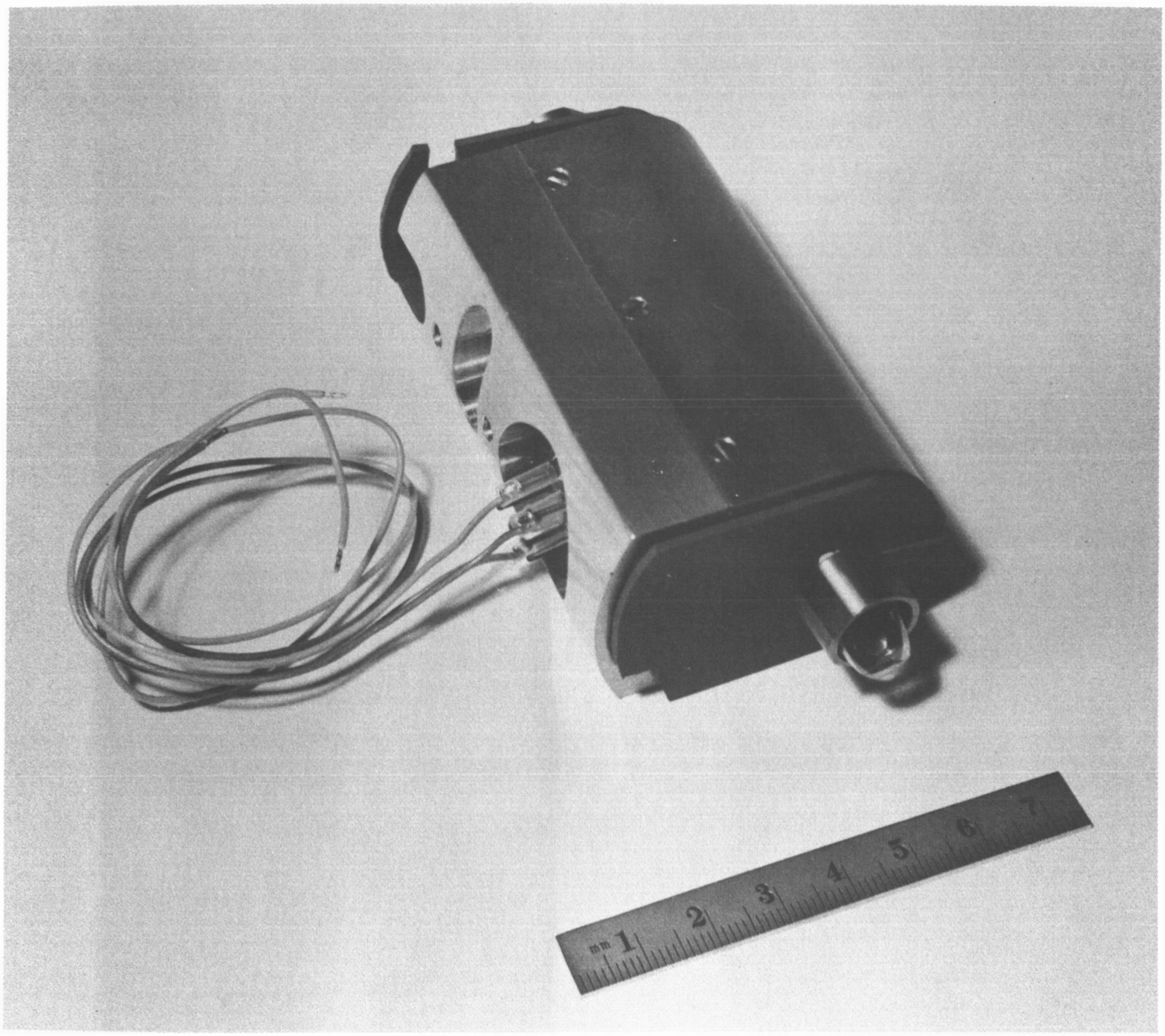


Figure 2. Plasma Tube and Heat Sink Assembly With Air Shields

We have found that with reasonable care, DC plasma tubes can be operated free of plasma oscillations. For these reasons, it was decided to use DC excited plasma tubes for this quiet laser design.

Experience with large discharge tubes used in the argon-ion laser program at Perkin-Elmer suggested that by employing electrically isolated metal rings adjacent to the excited plasma, it would be possible to reduce noise and oscillations in the discharge. To test this hypothesis, two small He-Ne plasma tubes were built. The tubes had a 2 mm bore and were identical except that one had electrically floating aluminum rings inside the discharge tube adjacent to the plasma. Both tubes were tested for laser amplitude noise at various current densities and gas pressures while connected to the filling stations. Contrary to our expectations, no significant difference in noise was observed between these small tubes. This result was in contrast with an earlier observation made on larger tubes. We think that the improved performance observed in the large tube was probably due to the large electrical capacitance between adjacent rings. The small tubes made for this test had a much smaller capacitance between adjacent rings. The investigation was not pursued further.

The submarine type of plasma tube shown in Figure 3 was designed for quiet laser applications. These tubes require about 5 watts of cathode power and about 2 watts of anode power. It was found that when either the anode current or cathode current to this tube was varied, there were ranges of both quiet and noisy operation. Only one tube among the many fabricated was incapable of running quietly at any current settings. Heterodyning experiments of two independent lasers showed that when these tubes are operated in "quiet regions," there is no discernible FM plasma noise in the output.

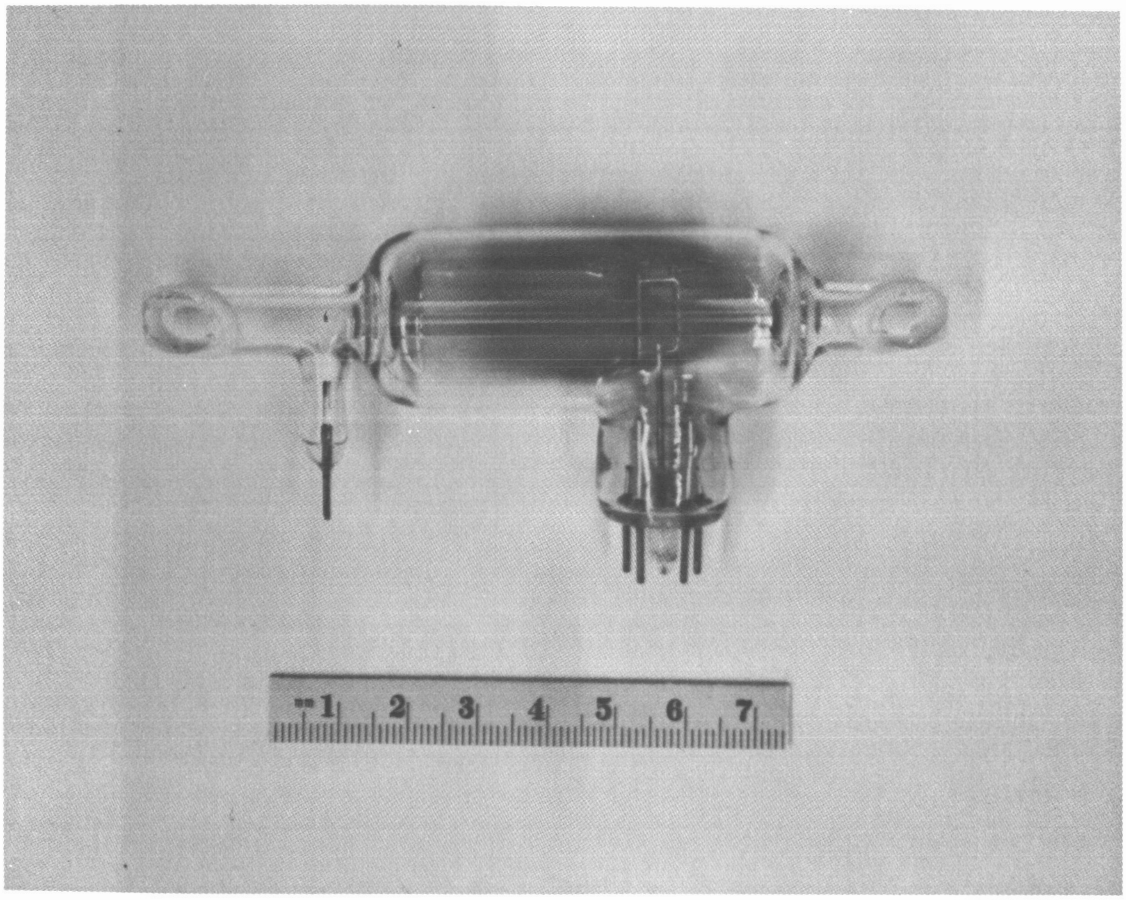


Figure 3. Plasma Tube

H. FREQUENCY PULLING AND MODE INTERACTIONS

Dispersion and competition effects in the active medium of a gas laser cause the optical frequency to vary with changes in laser power and plasma excitation. When the laser is slaved to an external frequency reference, the disturbances caused by the active medium are reduced by high loop gain of the control system. They do not significantly affect the stability of the closed-loop laser.

SECTION III

EXPERIMENTS AND RESULTS WITH BREADBOARD EXTERNALLY CONTROLLED LASERS

This section describes the stability measurements made on the externally controlled laser systems built under this contract, and discusses the factors which determine that stability.

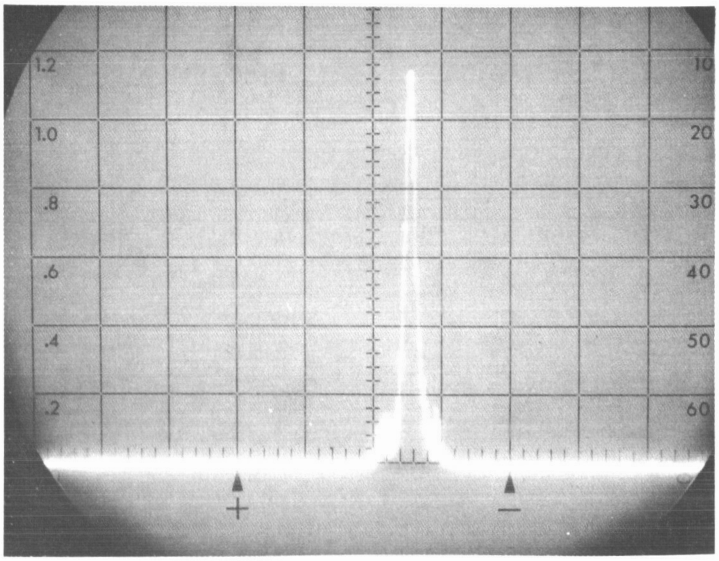
A. OPEN-LOOP STABILITY

The output beams from two laser systems (running open loop) were optically heterodyned and the stability of the beat frequency was measured. During these measurements, the lasers were thermally stabilized only. The beat frequency was observed to have a monotonic drift of between 2 and 6 MHz per hour which varied from day to day.

The linewidth of these open-loop lasers was approximately 15 kHz. Figure 4 is a photograph of the beat displayed on a panoramic spectrum analyzer. The horizontal scale is 100 kHz per division.

B. CLOSED-LOOP STABILITY

The first time the closed-loop lasers were set in operation, a disappointingly large drift rate of 60 MHz/hour was measured. This drift rate was caused in part by a pressure tuning mechanism connected to the hermetically sealed reference cavity. This tuning device was then disconnected and the cavities evacuated. The drift rate of the closed-loop systems immediately



Horizontal Scale: 100 KHz per Division

Figure 4. Beat Spectrum of Open-Loop Lasers

improved to 1/2 MHz/hour. Later, when the cavities were hermetically sealed without being connected to the vacuum pumps, the drift rate increased to several MHz per hour, presumably as a result of outgassing inside the cavity housing. An unsuccessful attempt was made to "clean" the cavities by baking under vacuum at 80°C. Because of epoxy in the cavity housing, these cavities could not be baked at higher temperatures. The systems were operated thereafter with the reference cavities connected to a vacuum pump.

Under continuous pumping, the system drift rate gradually improved to about 200 kHz per hour. This final drift rate was a factor of 15 improvement over the drift in the open-loop lasers. A chart recording of the closed-loop laser frequency versus time is shown in Figure 5. The horizontal scale is 5 minutes per division and the vertical scale is 1.5 MHz per division.

C. EXPERIMENTS TO REDUCE THE LASER LINEWIDTH

The reference cavity was illuminated for use as a Lipsett-Lee off-axis discriminator (described in Appendix B). This optical discriminator consists of an over illuminated off-axis, near confocal, cavity. Any change in the laser frequency results in a change in the beam direction of the light transmitted by the cavity.

A computer analysis was made to define the tolerances needed to construct a high finesse off-axis confocal resonator with a fixed non-adjustable spacer tube. For 100-mm radius mirrors, the analysis showed that the required length tolerance is ±0.002 mm. The complete results of that analysis are included as Appendix C.

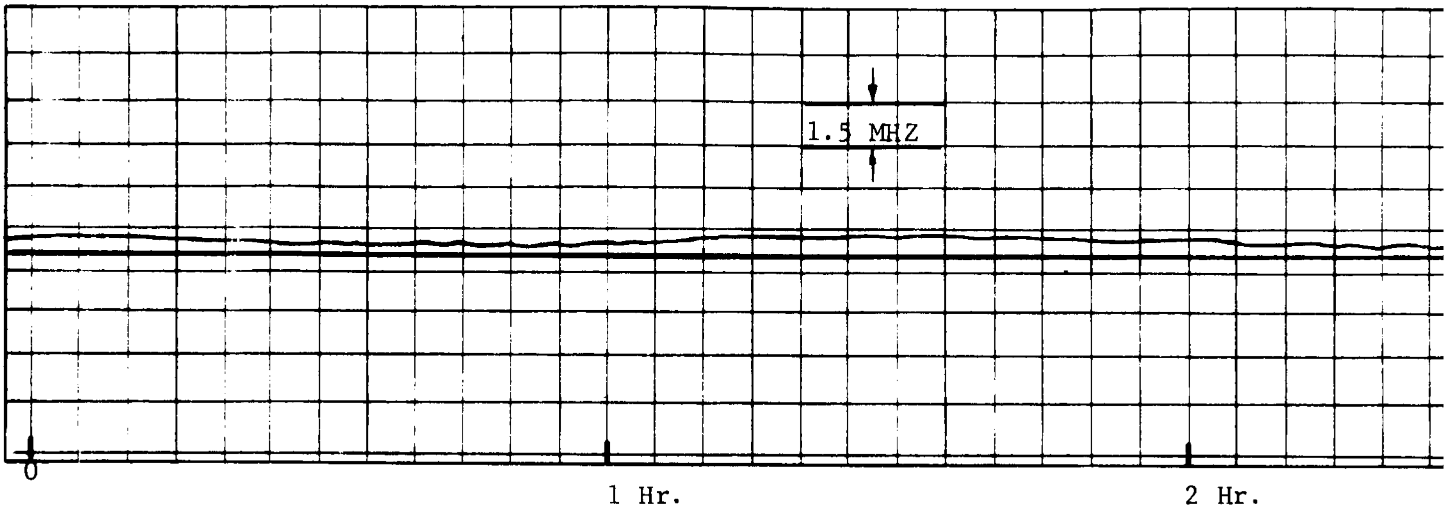


Figure 5. Stability Record of Closed-Loop Systems

Fabrication of the cavity spacer to this tolerance proved to be very difficult. The spacers, when finally completed, were 15 and 20 microns too short. This spacing error limited the cavity finesse to 30. For the 10-cm mirror spacing chosen, the finesse of 30 produced a cavity linewidth of 25 MHz. This linewidth, while broader than expected, was still narrow enough to reduce the laser linewidth as originally planned.

But, when the wide electrical bandwidth servo loop was closed, it was found to be microphonically sensitive. The reason for this sensitivity was explained by the fact that in a near confocal cavity the resonant frequency depends on the illumination geometry, as well as the mirror spacing. A 1-μ translation of the beam causes a 25-kHz frequency change. This microphonic sensitivity increased the laser linewidth because the closed servo loop converted vibrations of the illumination structure to FM in the laser output. The electronic bandwidth was then reduced so that this microphonic sensitivity did not broaden the open-loop laser linewidth.

It should still be possible to narrow the linewidth of our quiet open-loop laser using a high gain, wideband servo referenced to a passive reference cavity. But, as this work shows, the cavity must be designed for minimum sensitivity to changes in the illumination geometry. Company-sponsored work on another program to develop an optical frequency standard has resulted in the invention of a discriminator which uses a cavity under such insensitive illumination conditions. This discriminator, like the Lipsett-Lee discriminator, also does not require modulating the laser frequency. It is described in Section V.

SECTION IV

DESCRIPTION OF THE BREADBOARD SYSTEMS

This section describes the stabilized laser systems built during this program. Although these systems are called "breadboards," stable laser construction per se requires considerably more engineering care than is normally expected in breadboards. For this reason, the "breadboard" lasers delivered to Marshall Space Flight Center approach being fully engineered systems.

Each breadboard system consists of a system housing and an electronics module. They can be operated as open-loop lasers, lasers controlled by external electrical signals, or as closed-loop stabilized lasers. Figure 6 is a block diagram showing the closed loop frequency control system.

Figure 7A shows the inside of the system housing. Each system housing contains a single mode He-Ne laser, a fused silica reference cavity, an optical train for generating the frequency error signal, and various ancillary optical components. The housings also contain the sensor and heaters required for the two-stage proportional temperature controller. The light output from the laser falls first on a beamsplitter (1) which passes 50 percent of the light for external use, and reflects the rest of the light through an aluminum tube (2) to a mirror (3). This light then illuminates the resonant cavity (4). It leaves the cavity only for frequencies near resonance, and then in a direction dependent upon its frequency. This output beam from the cavity passes in turn through the split plate (5) and quarter-wave plate combination, and finally

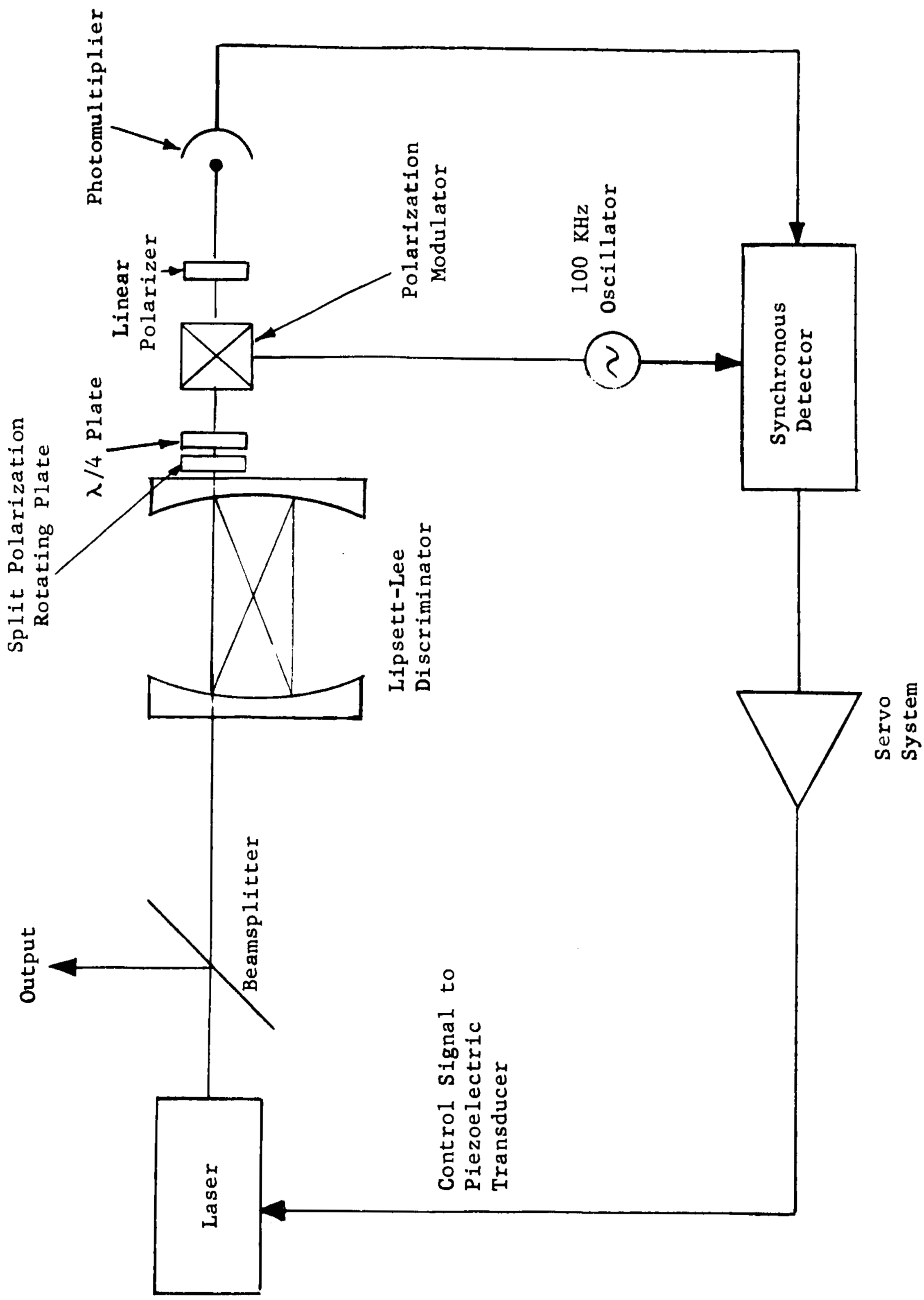


Figure 6. Closed Loop Frequency Control System.

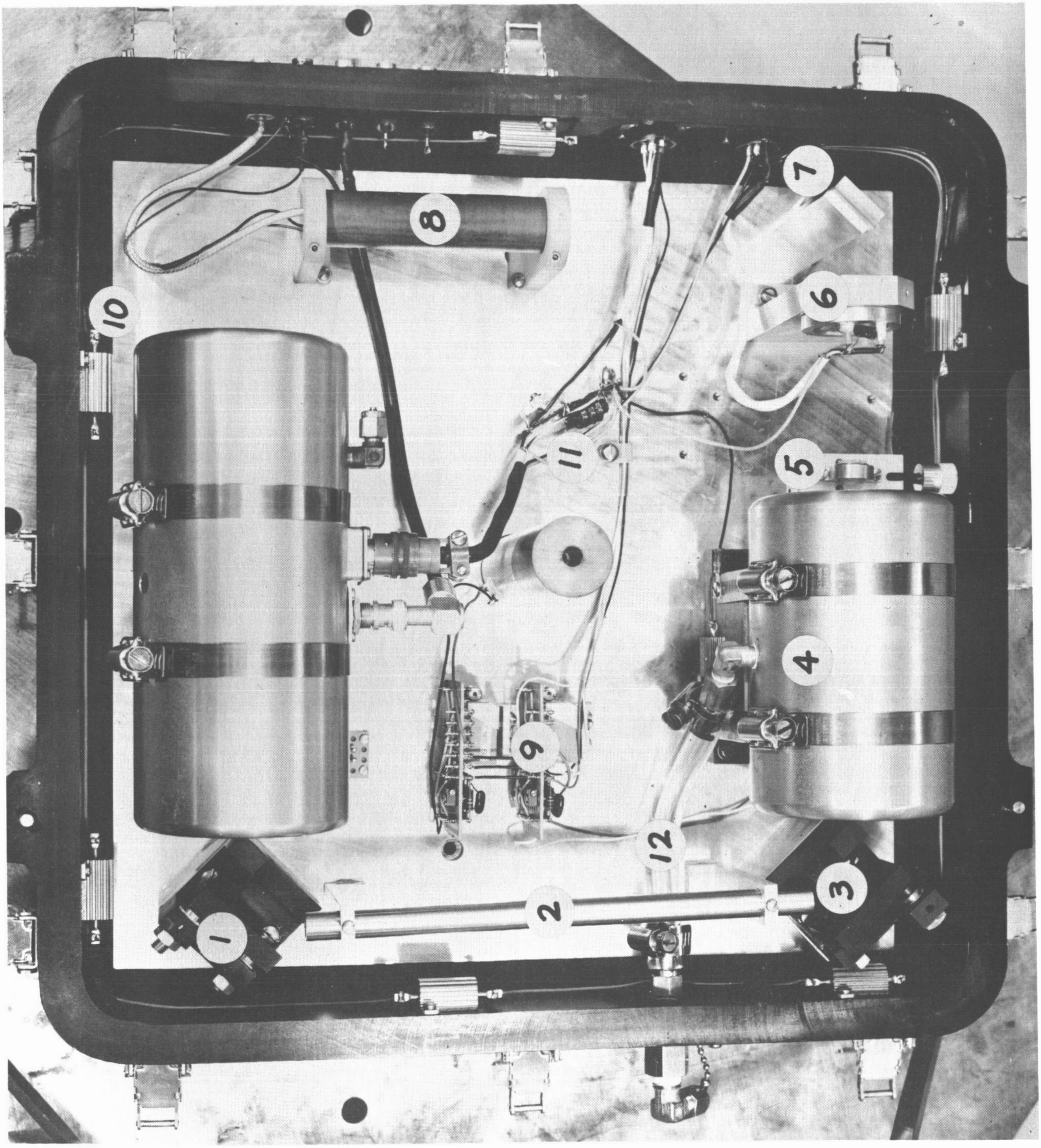


Figure 7A. System Housing Layout

through the modulator and tandem polarizer (6) before being reflected by a mirror (7) into the photomultiplier (8). The split plate is mounted on a movable slide. Also shown in this photograph (Figure 7A) are the two thermistor bridges with preamplifiers (9), the six outer case heaters (10), and the 100-kHz pusher filter (11), and the vacuum pump connection tube (12). The closed housing is shown in Figure 7B.

Before discussing the operation of the system in more detail, the major components will first be described:

A. LASER

The resonator of the helium-neon laser has a 13.5-cm mirror spacing and two 120-cm-radius-of-curvature mirrors. This geometry restricts the laser oscillation to the fundamental transverse mode (TEM_{oo}) and for most tuning conditions, to one axial mode. The reflectivities of the mirrors greater than 99.9 percent and 99.5 percent, have been chosen to yield maximum power output (about 300μ watts) from one end of the laser.

The "submarine" plasma tube shown in Figure 3 is 10 cm long and has a bore diameter of 1 mm. Its construction with concentric inner and outer walls provides excellent rigidity and a large gas volume. This ballast volume and the use of a hot cathode (reduced sputtering) provide for long stable tube life. The tubes are filled with a single isotope, Ne^{22}, and operate at $\lambda = 6328\text{Å}$.

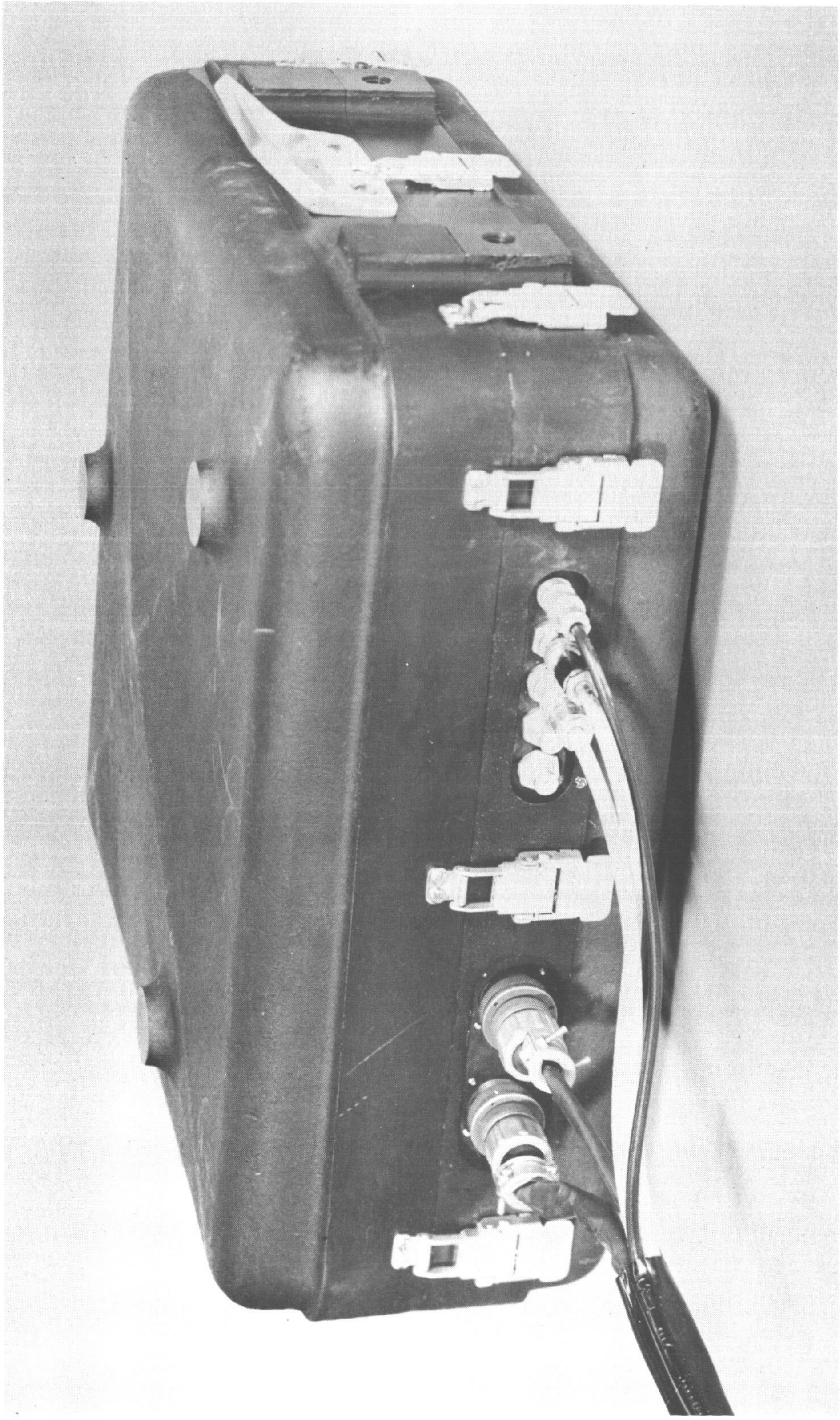


Figure 7B. System Housing

The laser resonator is machined from cast Invar which was chosen for its low temperature coefficient (5×10^{-7}) per °C. The ends have been ground flat and parallel, permitting alignment of the cavity mirrors without angular adjustments. For alignment, a small translation of the mirrors is made by sliding the end plates. Tightening the holding screws then locks the mirrors securely. This is shown in Figure 1. The plasma tube is held in the resonator at each end by three screws which bear on Invar collars attached to the tube.

The plasma tube is entirely surrounded by the copper heat sink and air shields shown in Figure 2. The heat sink is thermally and mechanically isolated from the Invar resonator. This enables the heat generated in the tube (about 8 watts) to be conducted directly to the outer casing without adversely affecting the resonator.

The entire resonator structure is housed in a thick-walled cylindrical aluminum case which has antireflection coated windows at both ends. This case is hermetically sealed and provides isolation of the laser against pressure changes. This is shown in Figure 8.

The laser frequency is tuned by a piezoelectric transducer which moves one of the mirrors. This transducer consists of a stack of four ceramic (PZT 5) wafers, mechanically in series and electrically in parallel, as is shown in Figure 9. These transducers have a tuning sensitivity of 3 MHz per volt.

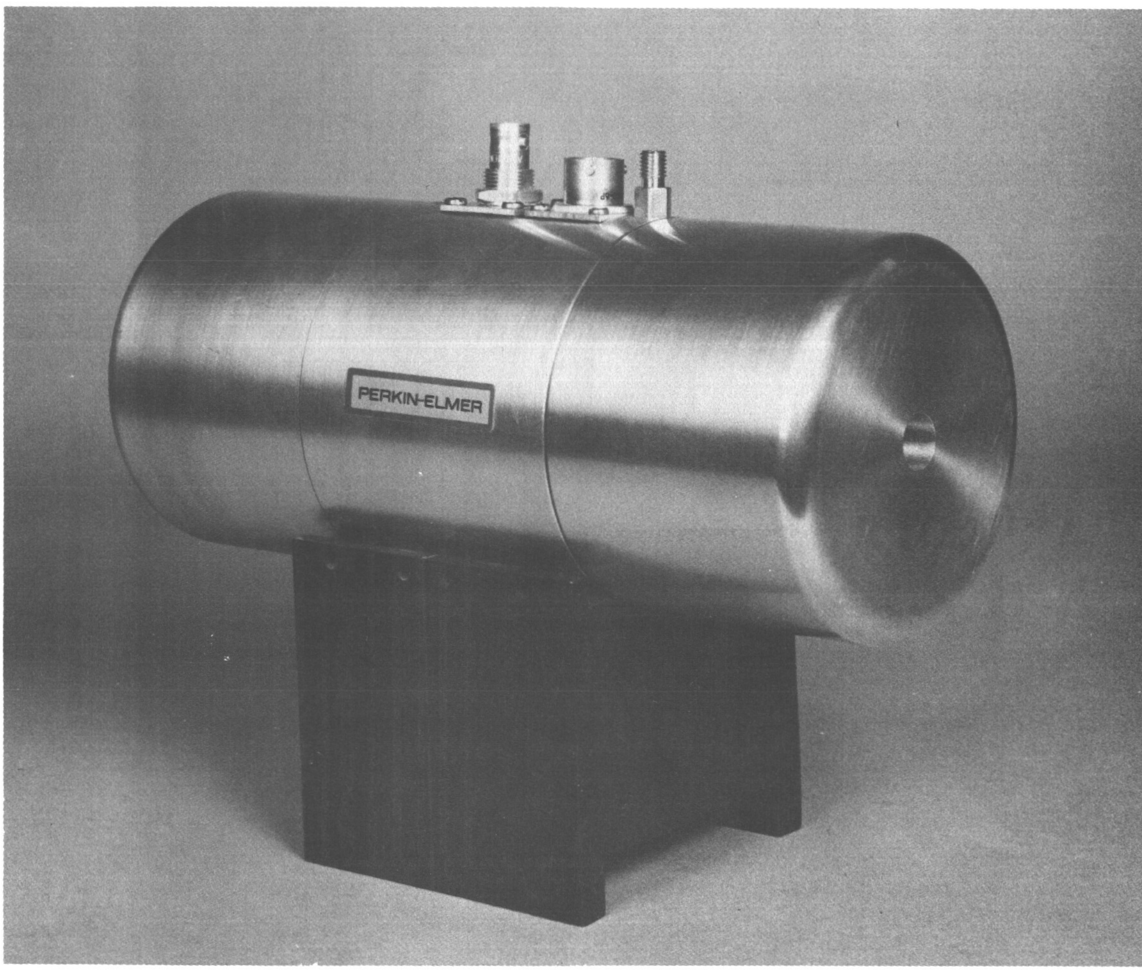


Figure 8. Laser Housing

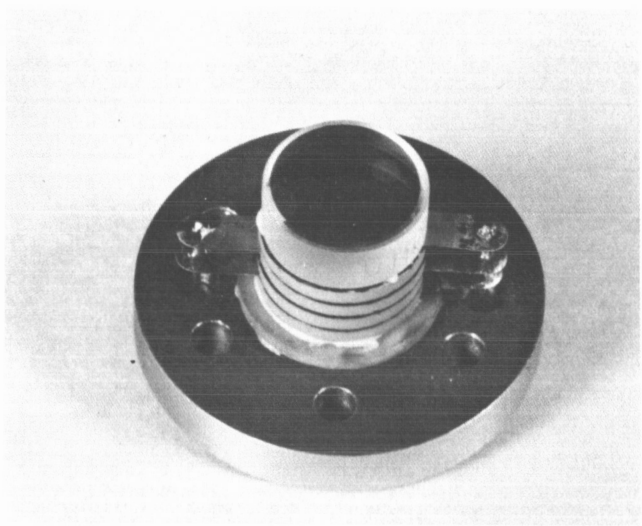


Figure 9. Laser Piezoelectric Mirror Transducer

B. REFERENCE CAVITY

The control systems use the reference element as a Lipsett-Lee off-axis discriminator. This discriminator, described in Appendix B, has two advantages over using the cavity as an on-axis discriminator. First, since it is a circulating resonator rather than a Fabry-Perot cavity, it eliminates the problem of back coupling between it and the laser cavity. Second, because frequency shifts in the laser result in changes in the output beam direction, it is not necessary to modulate the laser frequency over the resonance (as in the "Lamb Dip" servo) to generate an error signal. This is important for the many applications where an unmodulated output frequency is desired.

The reference cavity is a fused silica structure with a mirror separation of 10 cm. It is of the same general shape ("negative dumbbell") as the laser resonator. A hole has been drilled along the axis for the light, and to the outside to connect the interior optical path between the mirrors with outside pressure. This resonator is shown in Figure 10.

The initial plan for building this resonator was to optically contact the mirrors to the ends of the spacer. Unfortunately, we then found that the optical-grade fused silica mirrors could not be contacted to the silica spacer which was more coarsely textured. We were forced to epoxy the mirrors to the spacer in a manner similar to that used for attaching Brewster-angle windows to laser plasma tubes.

The resonator is isolated within an aluminum housing similar to, but shorter than, that used around the laser. Both end faces of the housing

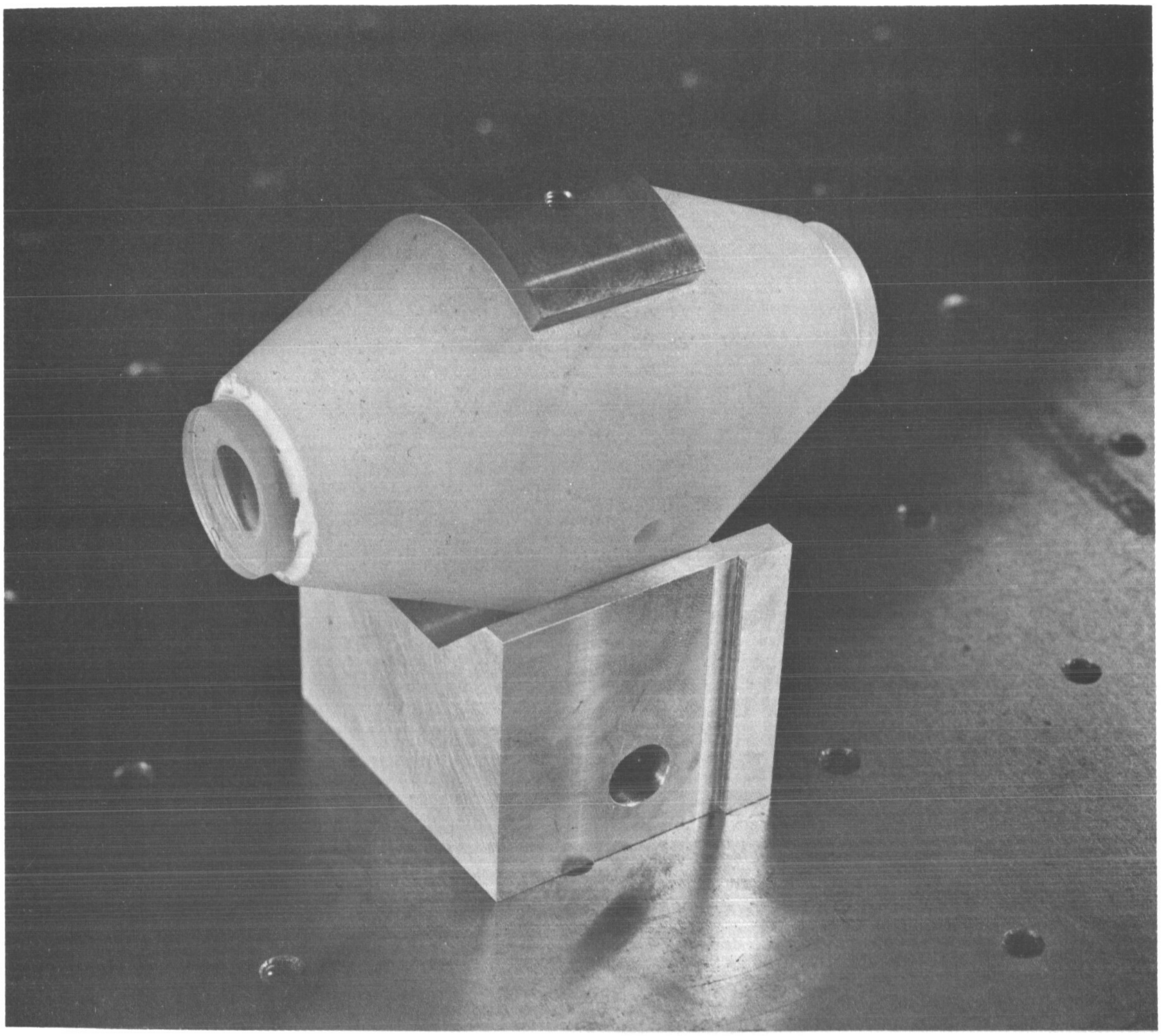


Figure 10. Fused Silica Reference Cavity

have antireflection coated windows for letting light in and out of the resonator. This housing is hermetically sealed and an evacuation fitting is brought out to the outer case.

C. OPTICAL TRAIN FOR DERIVING ERROR SIGNAL

A Lipsett-Lee off-axis discriminator results in a change of output beam direction when the frequency of the beam changes. This change in beam direction is converted to a frequency error signal by the optical train shown in Figure 11.

Light leaving the resonator is divided vertically into two orthogonally plane polarized components, shown in Figure 11, by a split polarization rotating plate. These components then pass through a quarter-wave retardation plate and are transformed to right and left circularly polarized components. The phase modulator produces two orthogonally plane polarized components which are switching at the modulation frequency. The intensity of each component depends on the intensity of the light transmitted by each half of the split plate and the phase of the modulation cycle. The light then passes through a linear polarizer oriented at 45 degrees to the plane polarized components.

If equal amounts of light are passing through the halves of the split plate, there will be no resulting intensity modulation during the course of the modulation cycle. If more light is passing through one half of the split plate then the other, there will be an intensity modulation. The phase of the intensity modulation with respect to the modulator drive signal, is determined by which half of the split plate is transmitting more light. The light now

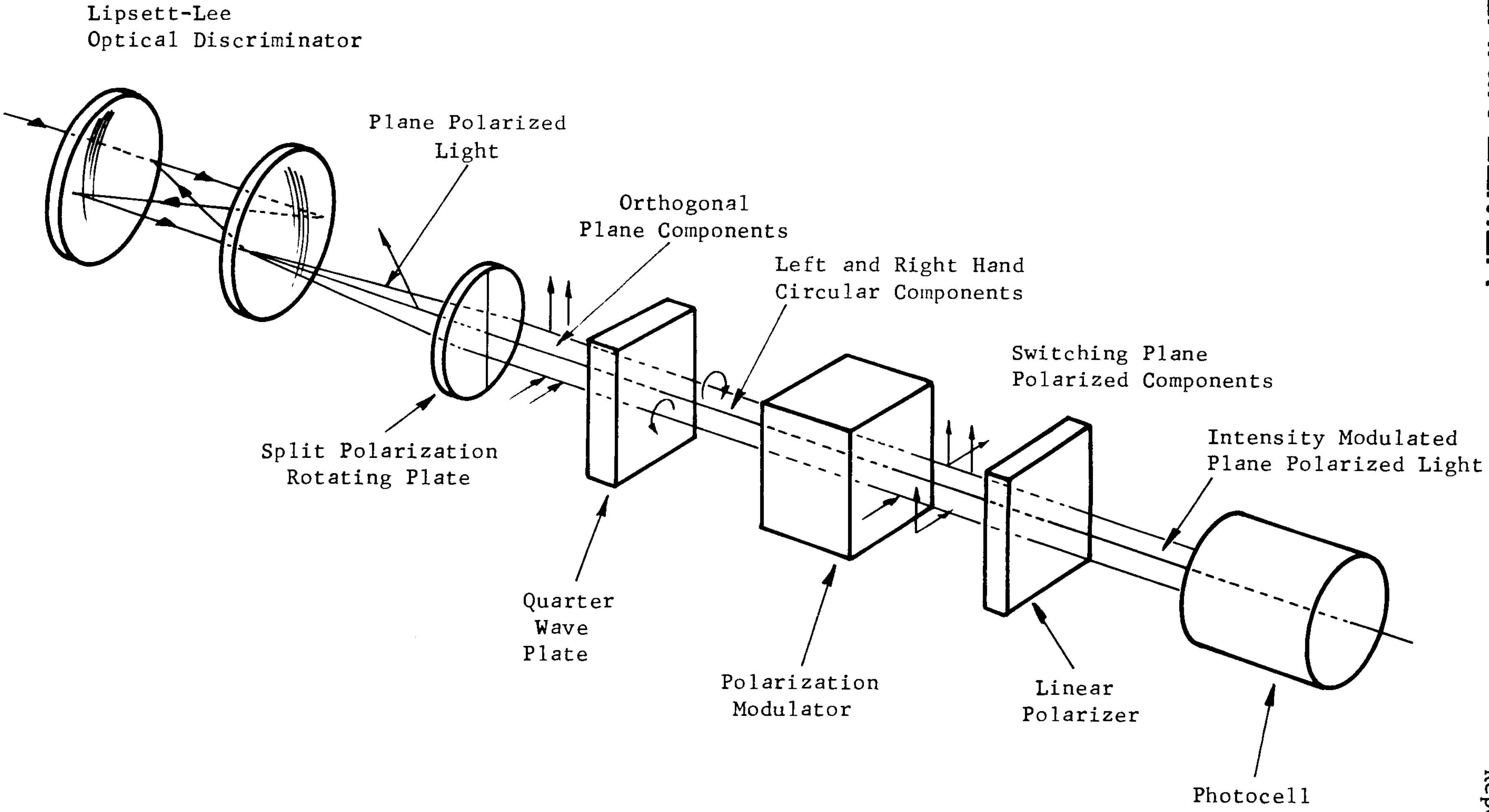


Figure 11. Optical Train For Generating Error Signal

falls on an RCA 8645 photomultiplier. All the information needed to derive the frequency error signal is contained in the photomultiplier output current.

The modulator consists of a 2-1/2-cm x 2-cm x 1-cm solid block of fused silica to which is cemented a piezoelectric wafer, driven at the mechanical resonance frequency. Driving the block at its mechanical resonance permits excitation of a vibrational mode using only a small amount of power. The vibration of this block results in alternate compression and expansion along axes perpendicular to the light path. This causes a strain induced birefringence which varies at the 100 kHz modulation frequency.

D. ELECTRONICS MODULE

The electronics module contains the laser power supplies, temperature controller electronics, the servo system for slaving the laser to the passive cavity, and various power supplies used for the entire system. The electronics module is shown in Figure 12. The uppermost panel contains the plasma tube power supplies which are controlled by the adjustments on the second panel from the top. The second panel from the top contains the photomultiplier power supply. The third panel from the top contains the photomultiplier power supply and is adjusted by its built-in control. The fourth panel from the top contains the proportional temperature controllers. Directly beneath the temperature controllers is the servo electronics panel. This panel is hinged at the bottom and opens for adjustments which are described in the operating instructions. The lowest two panels on the module are the 15-volt and 300-volt supplies, common to the entire system.

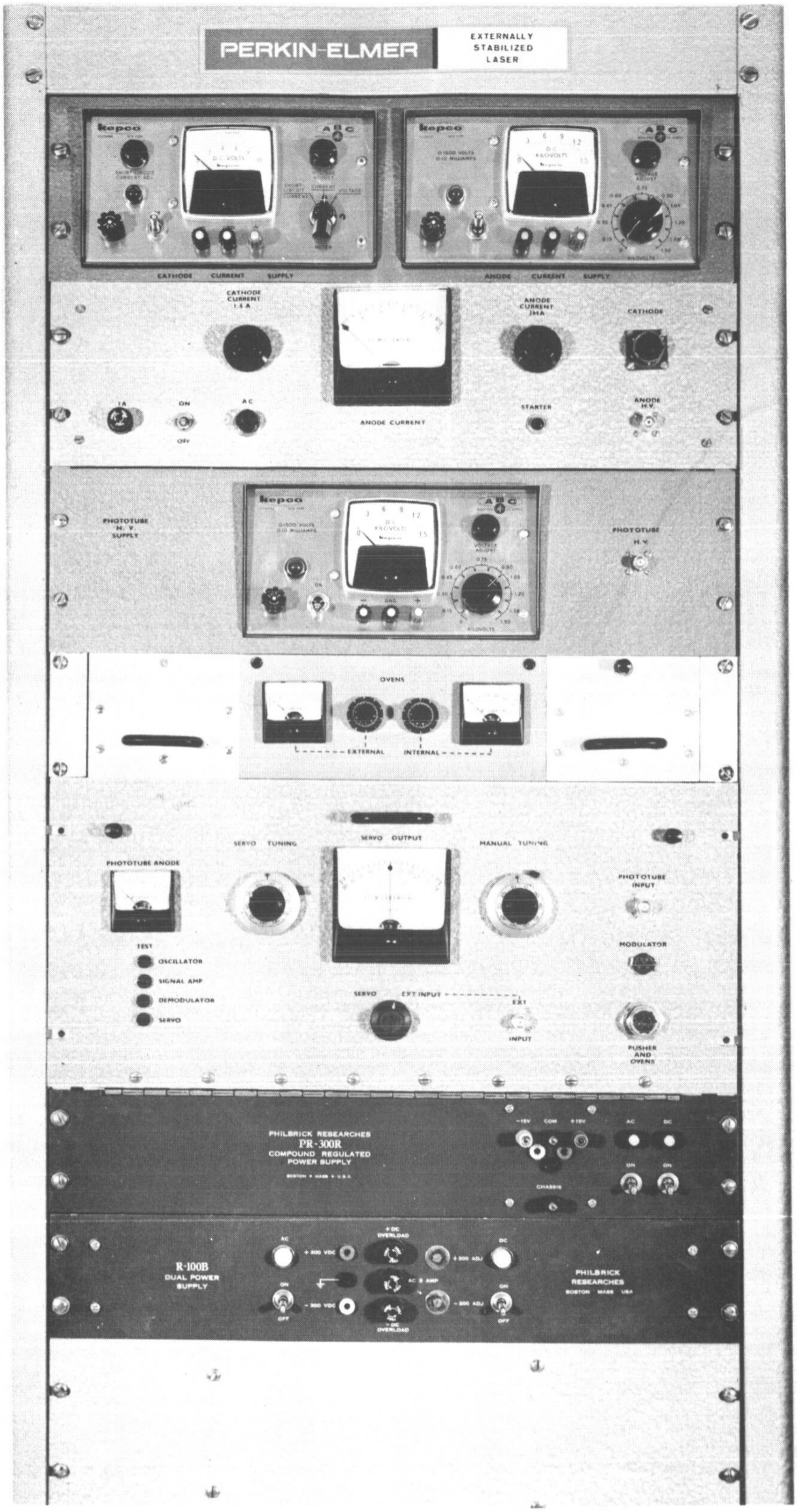


Figure 12. Electronics Module

The servo electronics package consists of the following circuitry:

1. 100 kHz modulator drive oscillator
2. Synchronous detector with a carrier frequency of 100 kHz, and bandwidth of approximately 1 Hz
3. Driver amplifier which is used to actuate the piezoelectric mirror transducer in the laser
4. Switching circuits to select each of the three modes of operation previously described

Figure 13 is a schematic diagram of the servo electronics system.

The servo electronics system has been designed for low noise and hum, and small DC drift. The range of the servo system (±300 MHz) is adequate to slave the laser to the reference cavity for a period of several days without resetting the laser frequency. Detailed circuit descriptions were delivered with the systems.

E. THERMAL CONTROL

Temperature regulation of the laser housing and the reference cavity is accomplished by a two-stage (tandem) proportional controller. The first stage adds about 50 watts of power to the large external system housing to raise its temperature about 15°C above the ambient. The second stage adds an additional 10 watts directly to the small reference cavity enclosure to raise its temperature about 10°C above the surrounding housing temperature. The amount of heat added to each stage varies in inverse proportion to the temperature measured by separate sensors. The residual temperature drift is probably about ±0.005°C per hour. This is caused in part by instabilities of the thermistor sensors, and in part by residual thermal gradients.

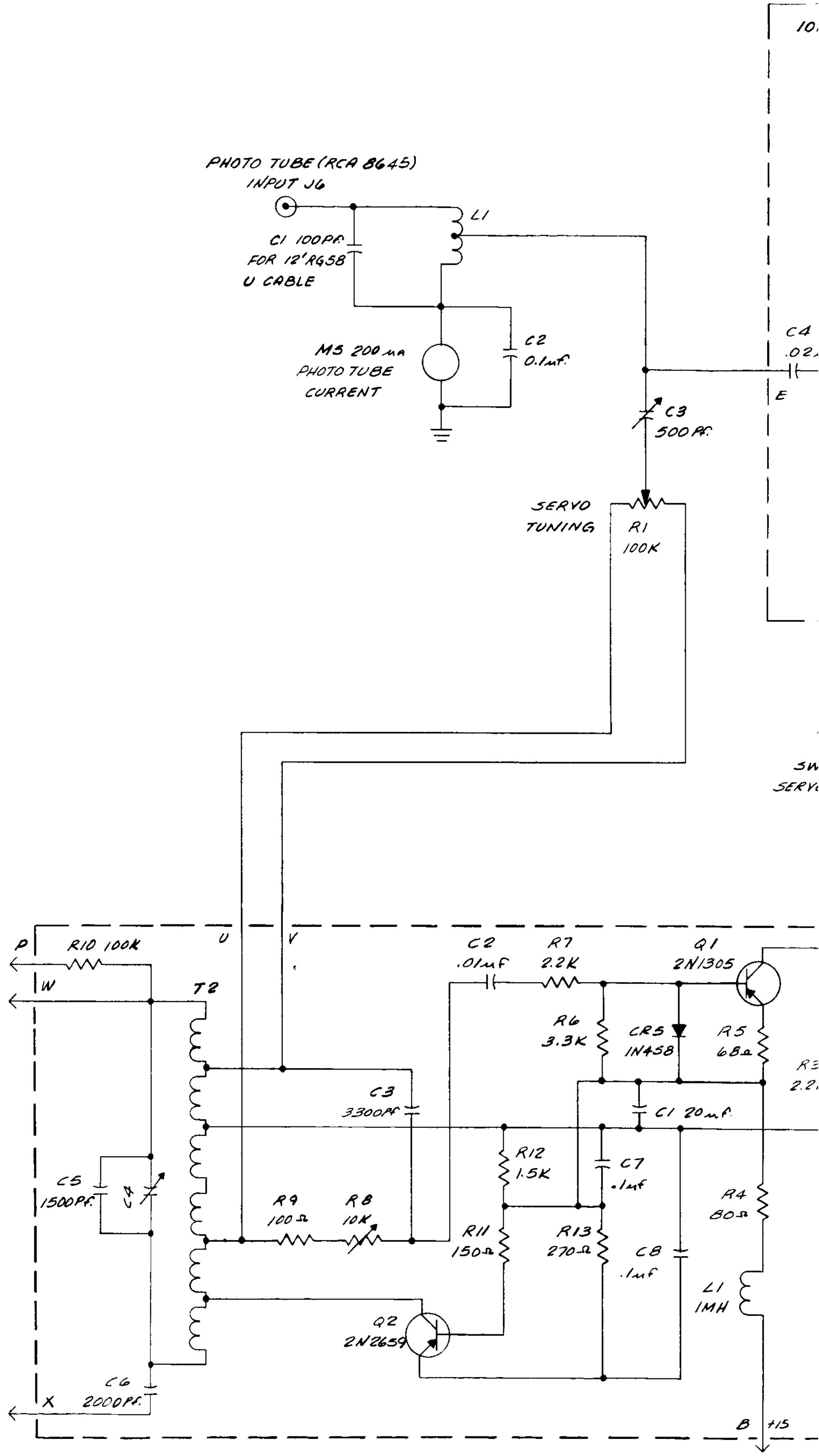
F. SYSTEM OPERATING CHARACTERISTICS

Stable operation requires that temperature regulation be established. The lasers require about 24 hours to come to thermal equilibrium. For open-loop mode operation, the lasers can be manually tuned (piezoelectrically) by the manual tuning control on the servo electronics panel. This control is a ten-turn potentiometer and has a range of about 1800 MHz (1.5 orders). After changing the setting of this control, it is necessary to wait several minutes until the small residual drift in the lasers (caused by lag in the piezoelectric transducers) dissipates. This drift is not significant when the lasers are operated in the closed-loop mode.

The lasers can also be controlled by externally applied electrical signals. In this mode, the laser frequency is determined by both the manual tuning control and the dc coupled external electrical signal in combination. The sensitivity to external signal is 30 MHz per applied volt. Voltages as high as ±10 volts can be used. AC signal frequencies up to 1 kHz can be used.

The closed-loop mode of operation uses a servo system with a high DC loop gain which drops 12 db per octave to unity at approximately 1 Hz. It is necessary to keep the reference cavities connected to a vacuum system and to maintain a pressure below 10 microns. There is a vacuum fitting on the system housing for this purpose. The steps required to close the servo loop are described in Appendix A.

While the lasers are operated in the closed-loop mode, they can still be piezoelectrically tuned over a narrow range by the servo tuning control on the servo electronics panel. This control is a ten-turn potentiometer.



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C1 100PF.
FOR 12' RG58
U CABLE
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SERVO
TUNING
R1
100K
C4
E
P
R10 100K
U
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W
T2
C2
.01uf
R7
2.2K
Q1
2N1305
R6
3.3K
CR5
1N458
R5
68Ω
C3
3300PF
C1 20uf
C5
1500PF.
C4
R12
1.5K
C7
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R8
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B
+15

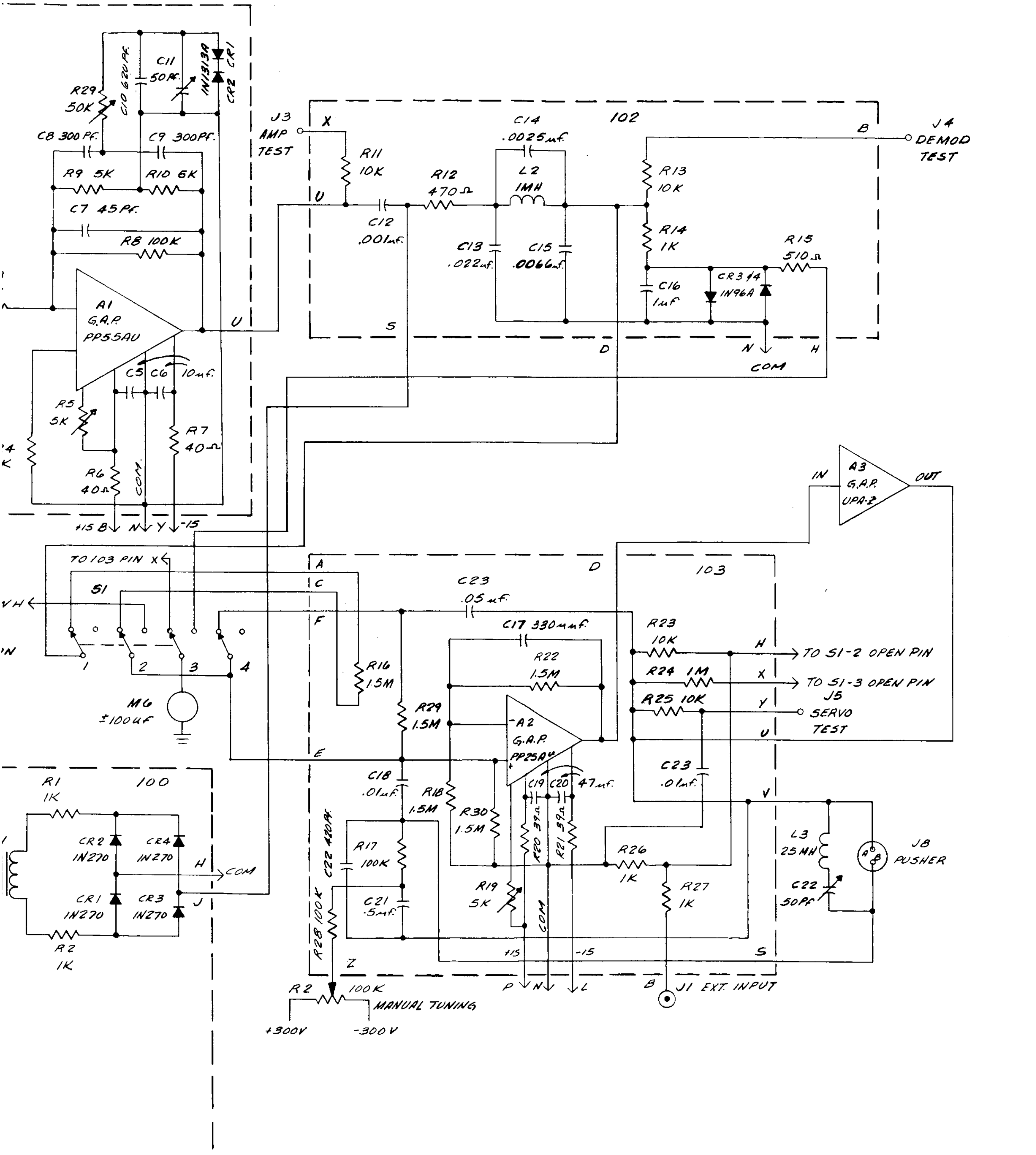

Figure 13. Schematic Diagram Of Servo System

It can tune the laser over a range of ±5 MHz from the center frequency of the cavity resonance.

This form of stabilized laser system has an unmodulated output frequency which increases its usefulness for many applications.

SECTION V

RECOMMENDATIONS BASED ON THIS STUDY

The Perkin-Elmer approach to making a stable laser system is first to make an open-loop laser of the highest practical stability. The frequency of this laser is then slaved to the resonance of a passive cavity (interferometer) which has been specifically designed for excellent short-term stability.

The limitations imposed by the broad atomic linewidth and inherent structural instabilities in the helium-neon laser, make it possible to build a laser system with better short-term stability by using an external reference element. The systems developed to date should be considered as a first step towards still more stable laser systems using external reference elements. We have learned from this program that this approach is sound, and that many aspects of this first system can be much improved.

The drift rate of the closed-loop lasers, while significantly better than the best open-loop lasers, is limited by the instabilities of the reference element. Within the scope of the program we were unable to develop more stable cavities. We believe that further engineering of reference elements will surely result in the development of more stable sealed cavities. A linewidth of 1 MHz should be realized in these cavities.

To date, no one has reported success in reducing the high-frequency disturbances in a reasonably quiet laser by using a wide electrical bandwidth control system. To make such a system will require an optical discriminator which is not microphonically sensitive. It is also desirable that any optical discriminator not require modulation of either the laser frequency or the reference cavity resonant frequency.

A new optical discriminator which satisfies the requirements above should soon be available. This discriminator is based on the rapid phase shift of the light transmitted by a passive cavity near resonance.

Figure 14 shows the optical transmission through a resonant cavity as a function of frequency. Figure 15 shows the optical phase shift as a function of frequency of the light passing through the identical resonant cavity. Unlike the transmitted intensity, the phase shift is antisymmetrical about the resonance center. This phase shift can be used to generate a frequency error signal and thus avoid modulating either the laser or cavity.

The passive reference element used in a phase sensitive discriminator can be a large-radius mirror cavity illuminated on axis. For a configuration of this type, the resonant frequency is relatively unaffected by the laser illumination geometry.

To make a discriminator which is sensitive to the phase shift through a resonant cavity, it is necessary to provide a reference lightbeam which later interferes with the light from the cavity. A two-arm interferometer (Mach-Zehnder) can be used as the necessary phase measuring bridge. One bridge arm contains a passive cavity illuminated on axis. The other arm serves as the phase reference and contains the modulator. Phase differences then result in intensity variations which can be detected by a photocell.

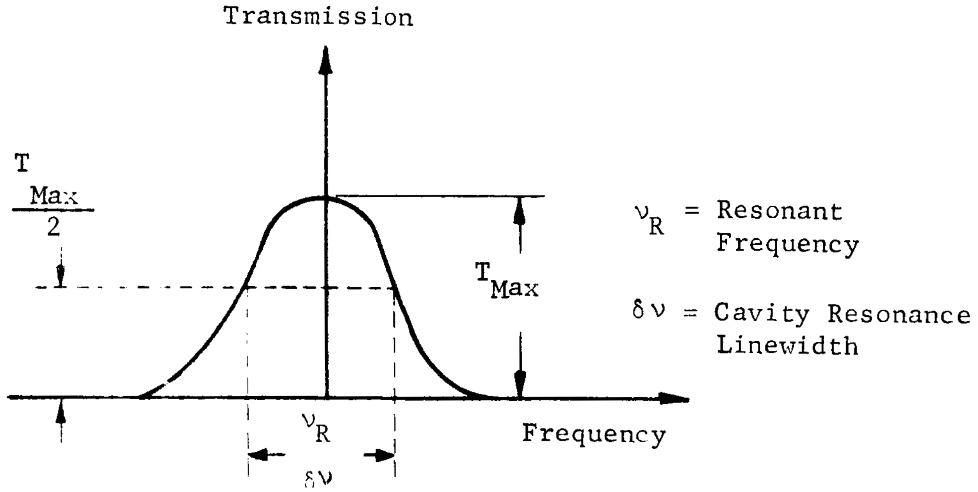

Figure 14. Transmission of a Passive Cavity

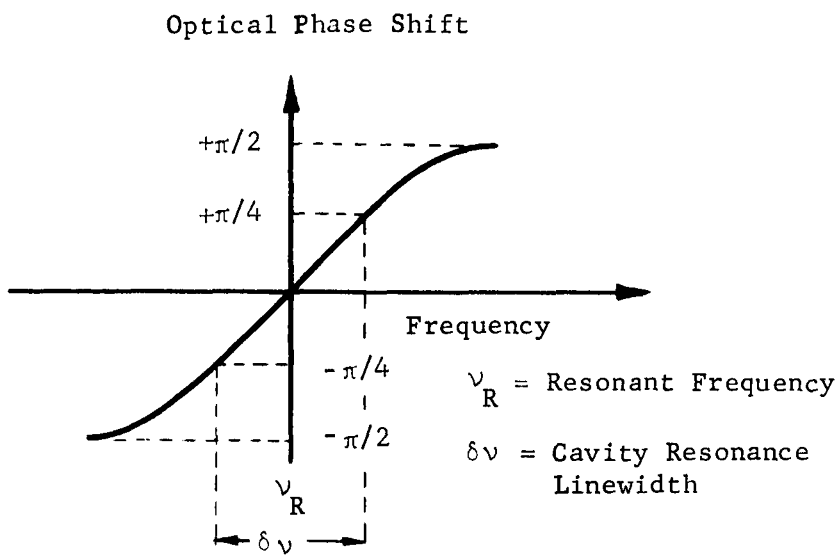

Figure 15. Optical Phase Shift of a Passive Cavity

An experiment to generate the required frequency error signal using a bridge of this type was performed. A description of the experiment is found in Appendix D, a preprint of correspondence to be published in the December 1966 Journal of Quantum Electronics.

A difficulty in making a low noise control system is the common need for the system to maintain its control of the laser frequency for periods as long as 1000 hours. The drift rate of the open loop lasers developed is about 3 MHz per hour. A laser frequency control system should, therefore, have a range of 3000 MHz. The dynamic range of electronic devices must not restrict the design of such a servo system. The requirements of a servo system are that the noise and hum modulation it introduces on the laser be small compared to the stability that is desired. For a wide bandwidth system this could be 100 Hz. This would require that the noise of a servo system be 3×10^{-8} of its range. This is difficult to obtain in a single-stage system.

A solution to this problem is to use a two-speed servo system. One narrow band loop has the 3000-MHz tuning range desired, but it need have only a low bandwidth above DC. The second wideband servo loop has a high frequency response but needs only a limited tuning range.

A redesigned open-loop laser with two independent pushers, each controlled by a separate amplifier in a woofer-tweeter combination, can be used with the two-speed system. Experiments with piezoelectric pushers used recently show that some types can be used to frequencies as high as 30 kHz.

We recommend that a second generation of significantly improved externally stabilized lasers be developed. On the basis of the experience of this program and other programs at Perkin-Elmer, we believe that it is practicable to reduce the linewidth of a laser to 1000 Hz (3 parts in 10^{12}) and also reduce the drift rate by employing an improved system such as the one described.

A diagram of such a feedback control system employing this phase comparison discriminator and a two-speed servo system is shown in Figure 16. The theoretical shot noise limited stability that can be achieved with a system of this type for a detector bandwidth, B, is derived to be approximately:

$$\Delta\nu \approx \sqrt{\frac{3\,(h\nu)\,B}{2\epsilon P}}\;\delta\nu$$

where

$\Delta\nu$ = shot noise stability limit

P = laser power

$\delta\nu$ = linewidth of cavity

ϵ = quantum efficiency of the photodetector

For the following parameters, this theoretically best stability is:

P = 100 microwatts

ν = 5×10^{14}

ϵ = 5×10^{-2}

$\delta\nu$ = 10^{6} Hz

B = 25 kHz

$\Delta\nu$ = 50 Hz

The technology developed in making external control systems for helium-neon lasers can be applied to similar systems for other kinds of lasers as well.

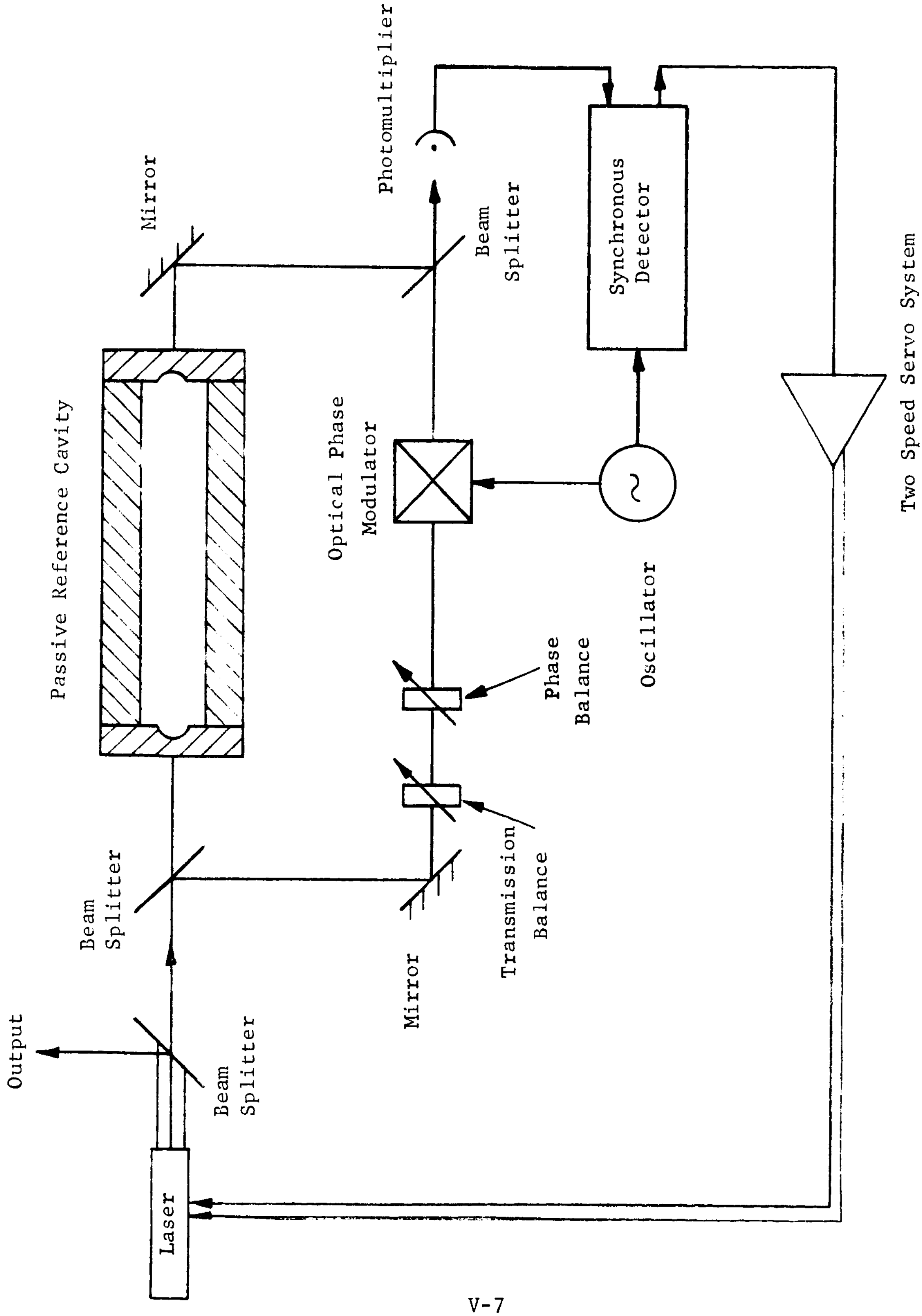

Figure 16. Laser Frequency Stabilization System

APPENDIX A

OPERATION MANUAL FOR THE EXTERNALLY CONTROLLED LASER

TABLE OF CONTENTS

OPERATION AND SERVICE MANUAL FOR

THE EXTERNALLY CONTROLLED LASER

I. INTRODUCTION

The externally controlled laser system consists of a single mode Helium-Neon laser, a passive resonant cavity, and the electronic circuitry required to slave the laser frequency to the cavity resonance. The laser housing and electronics module are connected together by the supplied cable. Each laser housing contains the laser, the reference cavity, the ancilliary optical components for generating a frequency discriminant, the photomultiplier tube, and two sets of thermistor bridges and heaters. The electronics module contains the servo electronics, two proportional temperature controllers, the plasma tube power supplies, and the power supplies required to operate the electronics. The purpose of this manual is to supply the information necessary to operate and maintain these systems. The experiments carried out under this program and a formal description of the systems designed and built thereunder are contained in the final report of this contract.

II. SPECIFICATIONS

Laser output power -	120 microwatts
Plane of polarization -	electric vector vertical
Laser wavelength -	6328Å
Open Loop Drift Rate* -	5 mHz/HR
Closed Loop Drift Rate ** -	200 kHz/HR
Linewidth* -	20 kHz

---

* Typical laboratory measurements.

** Reference cavities under vacuum.
Input power - 115 VAC-SINGLE PHASE - 3A.
Warm-up Time - 24 hours.

III. SYSTEM DESCRIPTION - LASER HOUSING

Figure 1 is a photograph of the inside of the Laser Housing. The light output from the laser falls first on a beam splitter[1] which passes 50% of the light for external use and reflects the rest of the light thru an aluminum tube[2] to a mirror[3]. This light then illuminates the resonant cavity[4]. It leaves the cavity only for frequencies near resonance, and then in a direction dependent upon its frequency. This output beam from the cavity passes in turn through the split plate[5] and quarter wave plate combination and finally thru the modulator and tandem polarizer[6] before being reflected by a mirror[7] into the photomultiplier[8]. The split plate is mounted on a moveable slide. Also shown in this photograph (Fig. 1) are the two thermistor bridges with preamplifiers[9], the six outer case heaters[10], and the 100 kH pusher filter[11]. The reference cavity housing is connected to the vacuum pump fitting by a short section of tubing[12]. Several differing adaptors are supplied with the system for connecting a vacuum pump to this fitting.

Figure 2 is a photograph of the laser housing with the cover on. It shows the five connectors attached. Whenever removing this cover it is important to make sure that the 0-ring which makes the acoustical seal is kept clean. When replacing two covers note that the systems are numbered and the covers are not interchangeable. Snap clamps should be released or taken up in rotation.

IV. SYSTEM DESCRIPTION - ELECTRONICS MODULE

The electronics module is shown in Figure 3. The power cord is shipped disconnected from the rear and is connected with a twist lock connector. The uppermost panel contains the plasma tube power supplies which are controlled by the adjustments on the second panel from the top. The controls on these supplies are normally left on and need not be used for shut down and start up. The third panel from the top contains the photomultiplier power supply and is adjusted by its built in control. Note: Even though the front panel binding posts of the plasma tube anode supply and photomultiplier supply are not used they still carry high voltages. The fourth panel from the top contains the proportional temperature controllers. Directly beneath the temperature controllers is the servo electronics panel. This panel is hinged at the bottom and opens for adjustments which are described in detail in a later section. The lowest two panels on the module are the 15 volt and 300 volt supplies, common to the entire system. The supply voltages can be measured using the test points on the front panel. The interconnecting cables to the laser head plug directly into the six connectors on the front of the module. Each of these connectors is unique except for the high voltage photomultiplier and anode connectors which are letter coded.

V. START-UP PROCEDURE

The instructions in this section assume that the optical alignment set and locked before shipment is still correct. It should seldom be necessary to adjust the optical alignment, but in the case of need the realignment procedure is discussed in a later section. The sequence below should be followed when starting from a fully shutdown condition.

1) After connecting the six cables between the laser housing and electronics module, turn on the back door circuit-breaker and the AC switch on the Philbrick R-100B (300 volt) power supply. This switch is shown as S1 in figure 4. This turns on the vacuum tube heaters in the servo amplifier and the heater current supplies for the internal (reference cavity) and external (laser housing) ovens. The oven current meters (M7 and M8 in figure 5) should then read about 75% and 50% respectively of full scale.

2) Turn on the AC switch of the Philbrick PR-300R (15 volt) supply shown in figure 4 as S2. This turns on the thermistor bridges of the proportional temperature controllers. When first turning the system on the oven current meters in figure 5 should show full output since the sensors will be calling for maximum heat. It is important to turn on the plasma tube and photomultiplier voltage before waiting for temperature equilibrium because these components are substantial heat sources within the laser housing. It is not necessary to use S3 except for applying the ± 15 volts to the front test points. <u>Note:</u> the oven time for asymptotic equilibrium is about 24 hours.

3) Turn on the AC switch in the plasma tube controller panel labeled S_3 in figure 6. The pilot light on this panel and on the cathode current supply (Kepco ABC 7.5-2m) will go on. Adjust the cathode current control R_1 in figure 6 for a cathode current of 1.6 amps. The cathode current is indicated on M_1 shown in figure 7. (Selector switch S_s set to current).

4) After the cathode has been receiving 1.6 amps for about 30 seconds the pilot indicator on the anode current (Kepco ABC 1500m) supply should light. The anode current supply is wired through a protection circuit which shuts it off unless the cathode supply is on, and the current is greater than 1.5 amps. The voltmeter on the anode supply (M_2 in figure 7) should read full scale at this time.

5) Turn the anode current control, R_2 in figure 6 fully clockwise and press the start button, S_4 in figure 6 to ignite the plasma tube. After the tube is ignited, adjust R_2 for an anode current of 3 mA indicated on the anode current meter M_3 in figure 6.

6) Turn on the photomutliplier power supply (Kepco ABC 1500m) and adjust initially for 1000 volts. This is indicated in M_4 of figure 8.

7) Switch the mode switch on the servo panel to the external position. This is S_5 shown in figure 9.

8) Turn on the DC switch of the Philbrick R100-B (300 volt) supply shown as S_6 in figure 4. The manual tuning control (R_3 in figure 9) can now be used to piezoelectrically tune the laser frequency. This control will tune the laser about 2.5 orders (1,500 MC per order) over its full range.

In this operating mode, the systems can now be used as open loop lasers without further adjustment. When the mode switch is in this external position the external input connector (J_1 in figure 9) can be used to control the laser frequency electrically. The input signal goes through a gain of 10 ($\pm$100 volt range) linear amplifier and is applied to the piezo-electric pusher in the laser. The external input connector is also used for sweeping the laser frequency for various applications including tuning adjustment of the servo system. This last use is described below.

The following steps are required for the adjustment of the servo electronics and should be made with an oscilloscope. These adjustments are made with the mode switch in the external position.

9) Connect an oscilloscope to the oscillator test point (J_2 in figure 9). Using a short screw driver adjust the modulator tuning capacitor (C_4 on circuit board 100) for maximum 100 kc signal. This capacitor is accessible through the hinged front of the servo panel. The adjustment location is shown in figure 10.

10) Adjust the manual tuning control (R_3 in figure 9) for maximum phototube current indicated on M_5 in figure 9. With this current held at maximum by the manual tuning control readjust the photomultiplier voltage for a phototube current of 100 μA.

11) Slowly rock the manual tuning control about the maximum phototube current position. A deflection (possibly small) will be seen on the error signal meter M_6 in figure 9. Adjust the modulator tuning capacitor (C_4 - figure 10) for maximum deflections.

12) When the manual tuning control is now tuned about the resonance the error signal meter should sweep over almost its entire range. This meter is now reading the output signal of the demodulator stage. This voltage is available for external measurement through the demodulator test point (J_4 in figure 9). If the deflection is not symmetrical about zero it is an indication of an optical misalignment. Optical realignment will be discussed elsewhere.

13) To close the servo loop, tune the laser through a resonance (with R_3) and when the error signal is near zero switch the mode switch (S_5) to the servo position. The error signal meter will now read near zero and the servo loop is closed. On switching to the servo mode, the error signal meter now reads the final output of the servo electronics i.e., the correction signal being applied to the laser pusher. The meter is now read $\pm$100 volts which is the range of the servo system. This is equal to approximately $\pm$600 mHz of laser frequency. To test simply for closed loop lock, slowly turn the manual tuning control R_3, and watch for a corresponding correction voltage to appear on the error signal meter; M_6.

14) Connect the oscilloscope to the signal amplifier test point (J_3 in figure 9). In the closed loop mode adjust the servo tuning control (R_4 in figure 9) for minimum 100 kc signal. Lock the dial. The laser is now locked to the center of the cavity resonance. Note the R_4 dial reading. To tune the laser frequency away from cavity resonance in the closed loop (servoed) mode the servo tuning can be unlocked and used to tune the laser about ± 5 mHz. After such use reset to the previously noted dial reading and lock the dial again.

VI. OPTICAL ALIGNMENT

When the error signal meter (with the mode switch in the external position) shows an asymmetrical discriminant optical misalignment is indicated. The frequency error signal is generated by measuring the position of the exit beam from the resonator. Consequently, changes in the optical components which change the position of this beam with respect to the split plate will change the discriminant. When properly aligned the exit light from the resonator consists of two spots in a horizontal plane. These spots move horizontally when the laser is tuned near the cavity resonance. For a description of the optical discriminator see appendix 2. When properly aligned the intersection of the split plate falls near the center of one of the spots, when this spot is at maximum intensity. When the laser frequency changes the spot moves from one side of this intersection to the other generating the frequency error signal. Only the spot containing the split plate intersection is reflected by the second mirror into the photocell.

The technique of alignment is first to make these spots appear in a horizontal plane. This is best accomplished by applying a 5 scan per second sweep to the laser frequency using the external input in the external mode. This sweep may be obtained from the sawtooth output from a Tektronix oscilloscope. A 50 kΩ resistor should be used between the sawtooth output from the oscilloscope and the external input connector on the servo electronics panel. With the laser frequency being swept the adjustment screws on the beam splitter mount and first mirror mount are used to illuminate the resonator on axis. In this condition the output single spot will blink on and off, but will not move in any direction. After this condition is obtained the horizontal adjustment of the beam splitter mount is used to change the output to the two spot mode. It will be observed that the two spots move horizontally as the frequency is swept. The illumination is proper when the spots are making the maximum horizontal travel during the sweep.

After the spots are moving in a horizontal plane the split plate is adjusted so that a dark band appears vertically in one spot. This spot is aimed at the phototube with the second mirror. It is important that only the spot containing the dark band falls on the phototube. This adjustment completes the visual part of the alignment procedure, the final alignment requires monitoring of the electrical signals.

After going through both the start up procedure and the visual alignment connect the oscilloscope to the signal amplifier test point (J_3 on figure 9). As the laser frequency is swept past the cavity resonance at a 20 scan per second rate a trace as shown in figure 11 should appear. It may be necessary to adjust the manual tuning control so the resonance falls within the sweep. If the envelope is larger on one side of the zero crossing than the other this can be rectified by readjusting the split plate position. The vertical scale of figure 11 is 1 volt/div.

After obtaining a trace similar to figure 11 connect the oscilloscope to the demodulator test point (J_4 in figure 9). A trace similar to that shown in figure 12 should appear. The vertical scale of figure 12 is 0.2 volts/div. The split plate is finally adjusted so that this discriminant is symmetrical about zero.

The final step in the optical alignment procedure is to tighten the set screws on the beam splitter and mirror mounts while watching the demodulator trace. This is necessary to make sure the mirror and beam splitter adjustments don't move when being locked.

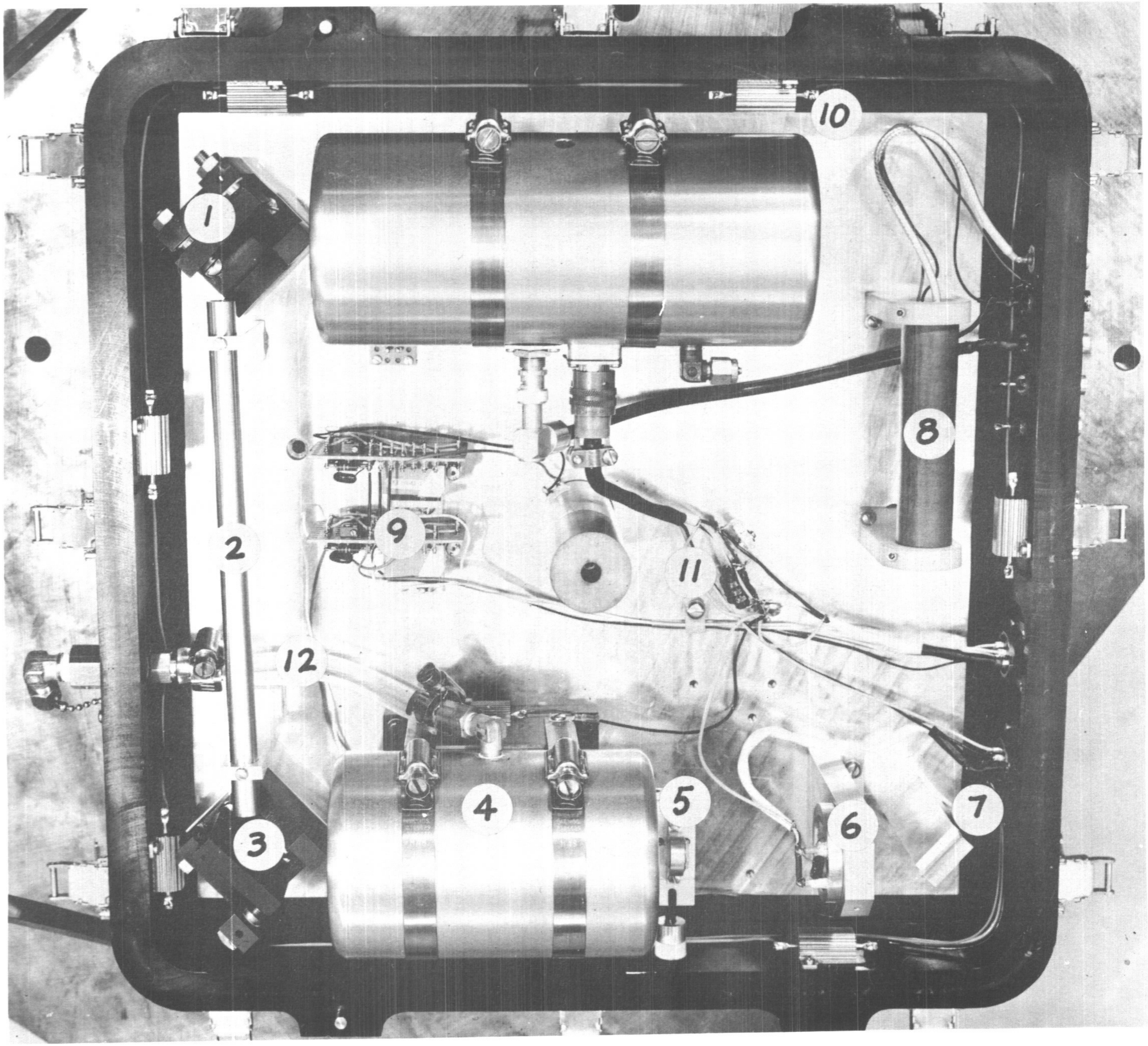

Figure 1. Laser Housing Layout

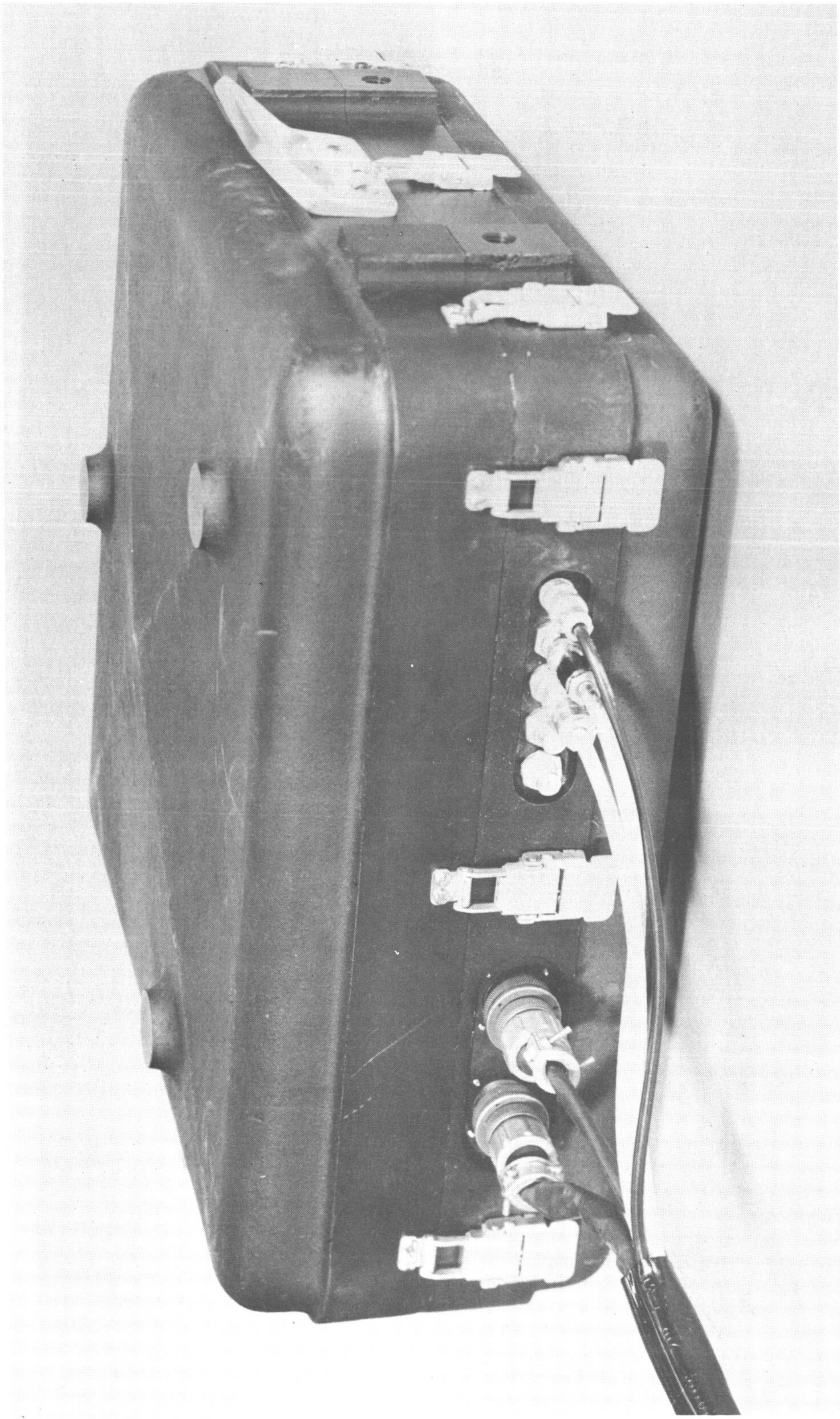

Figure 2. Laser Housing

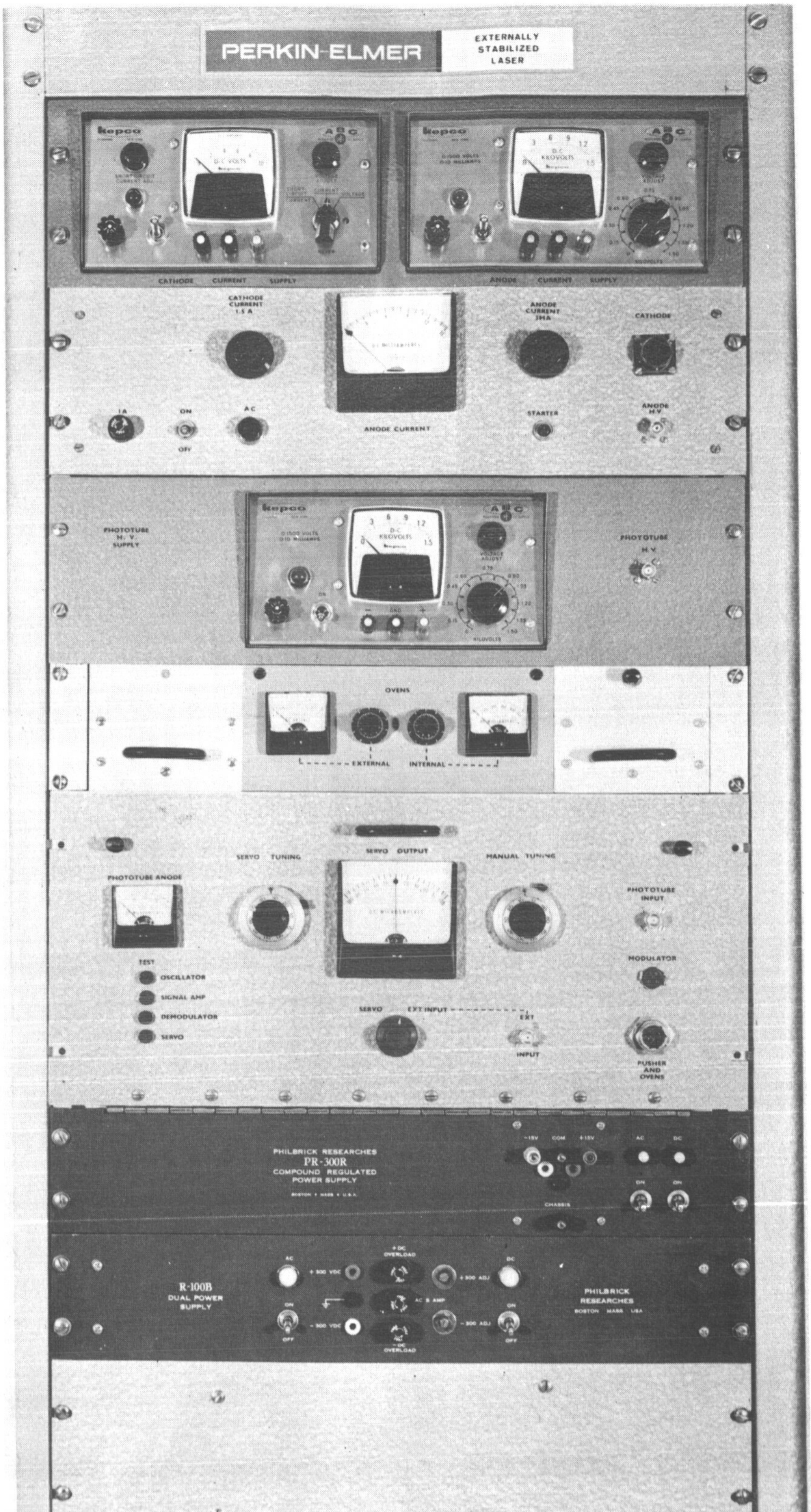

Figure 3. Electronics Module

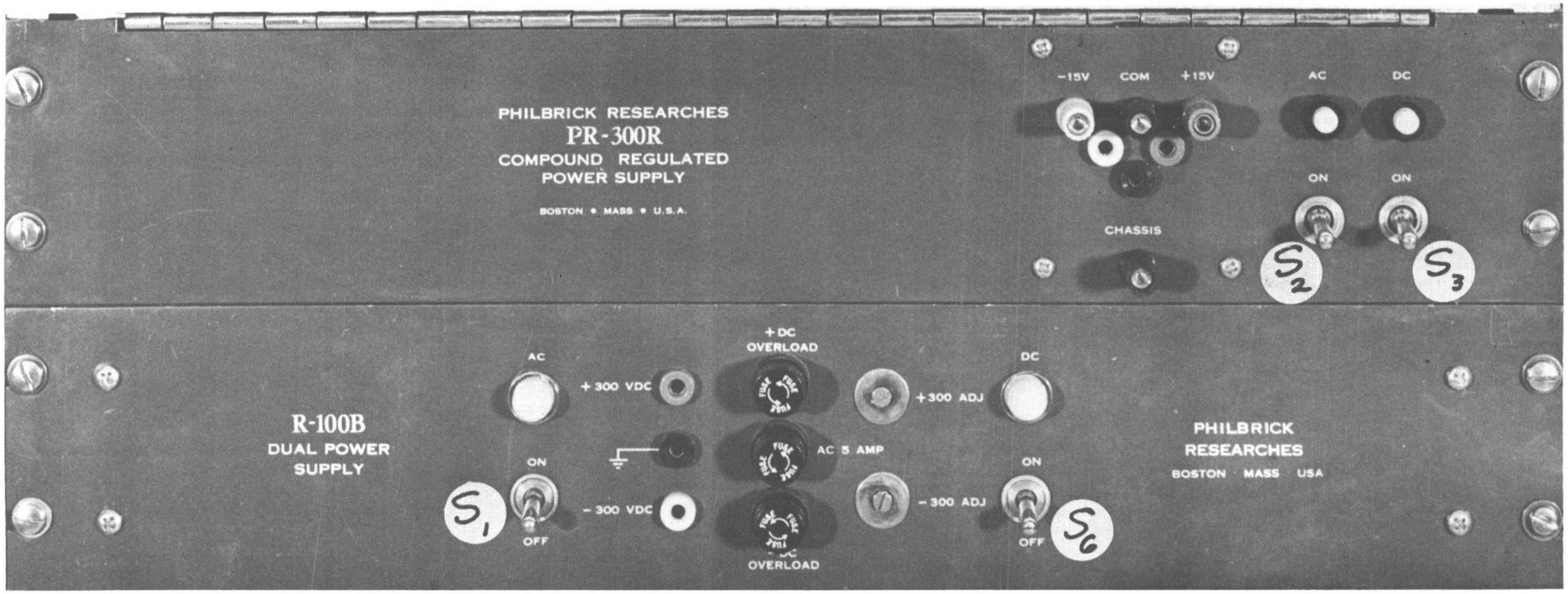

Figure 4. Philbrick Power Supplies

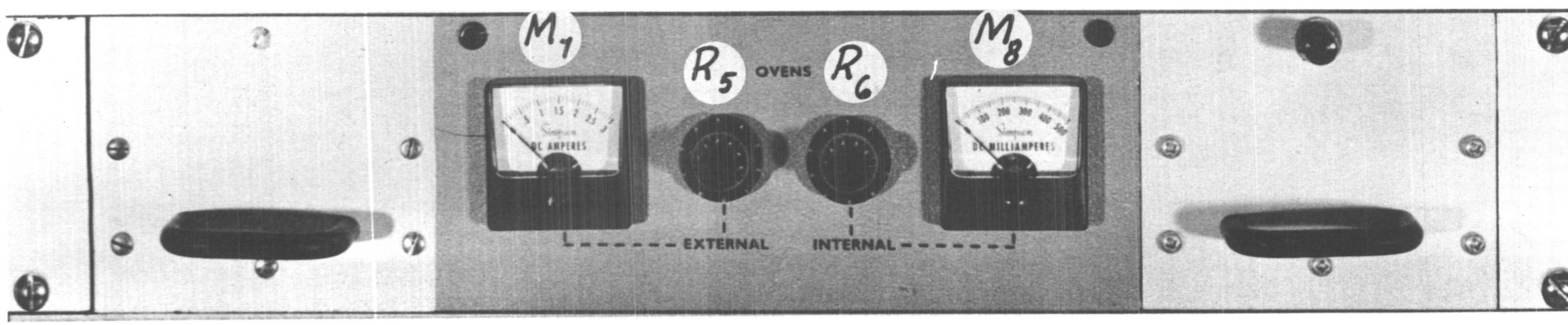

Figure 5. Oven Module

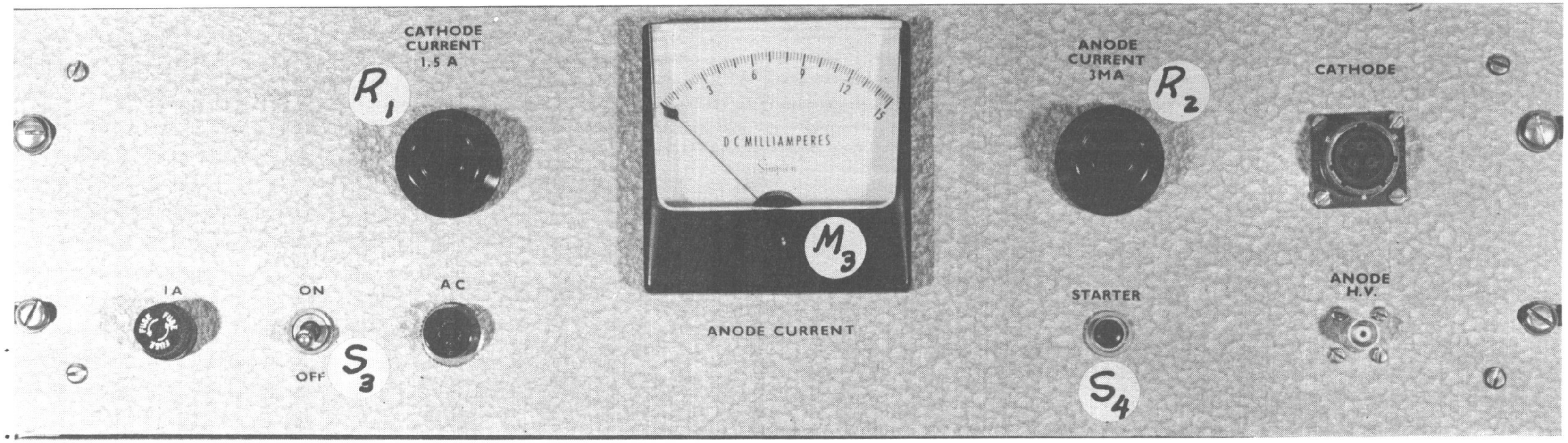

Figure 6. Plasma Tube Controller

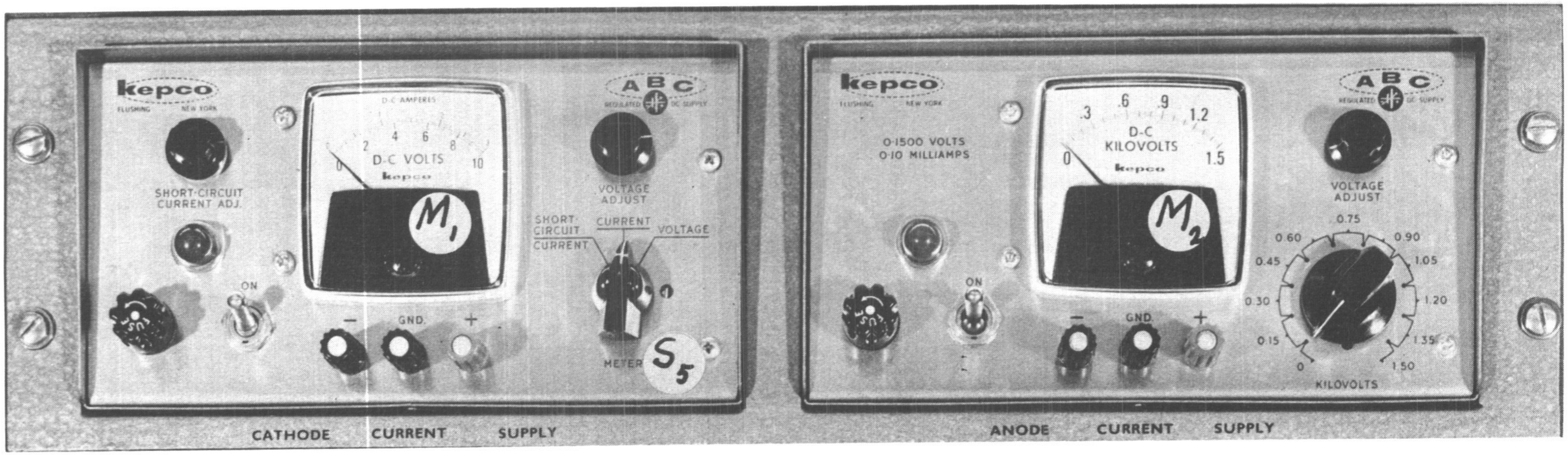

Figure 7. Kepco Plasma Tube Power Supplies

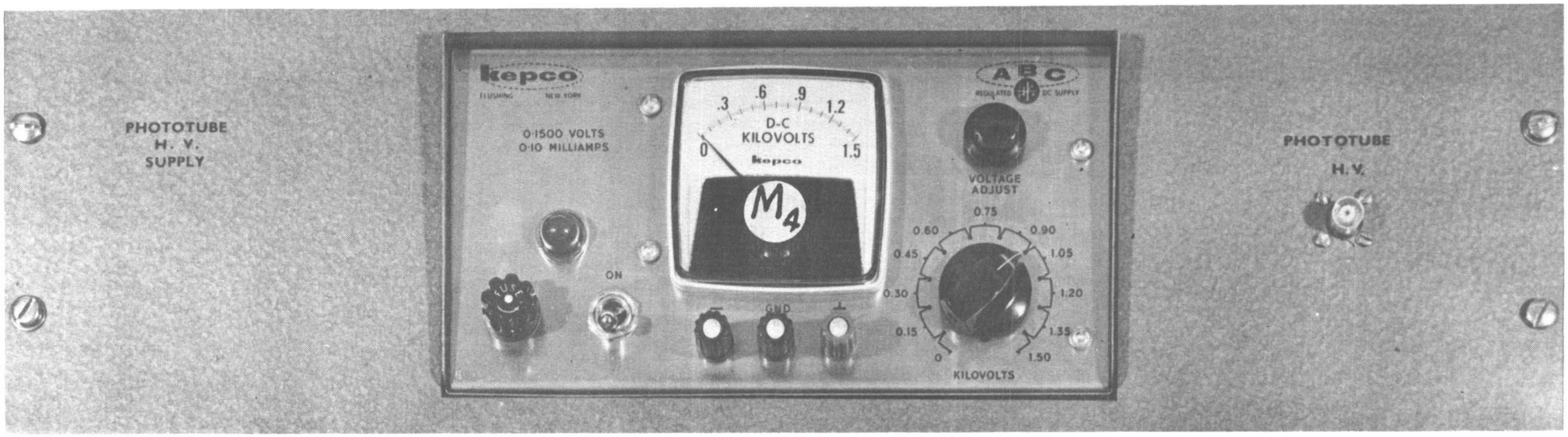

Figure 8. Kepco Photomultiplier Tube Power Supply

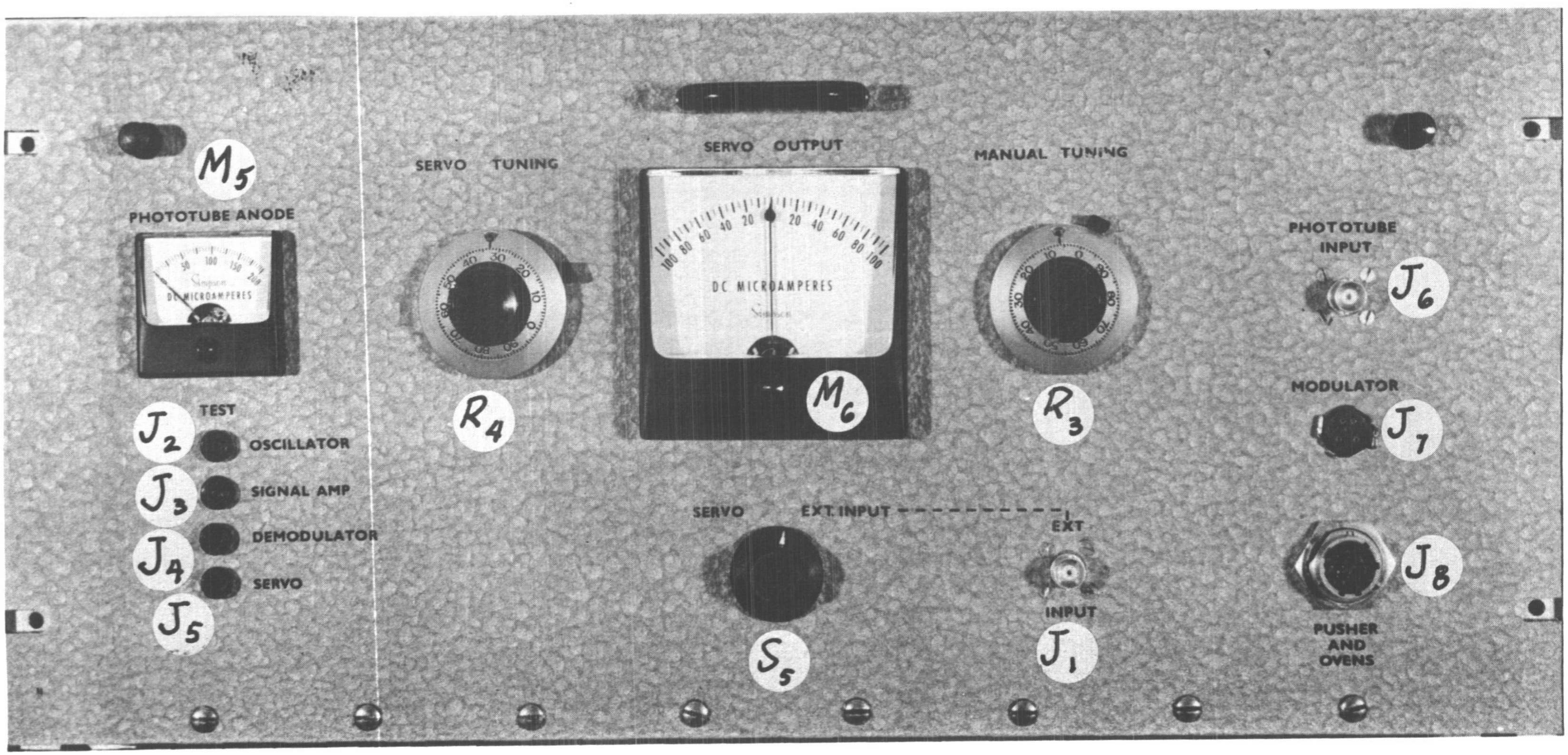

Figure 9. Servo Module

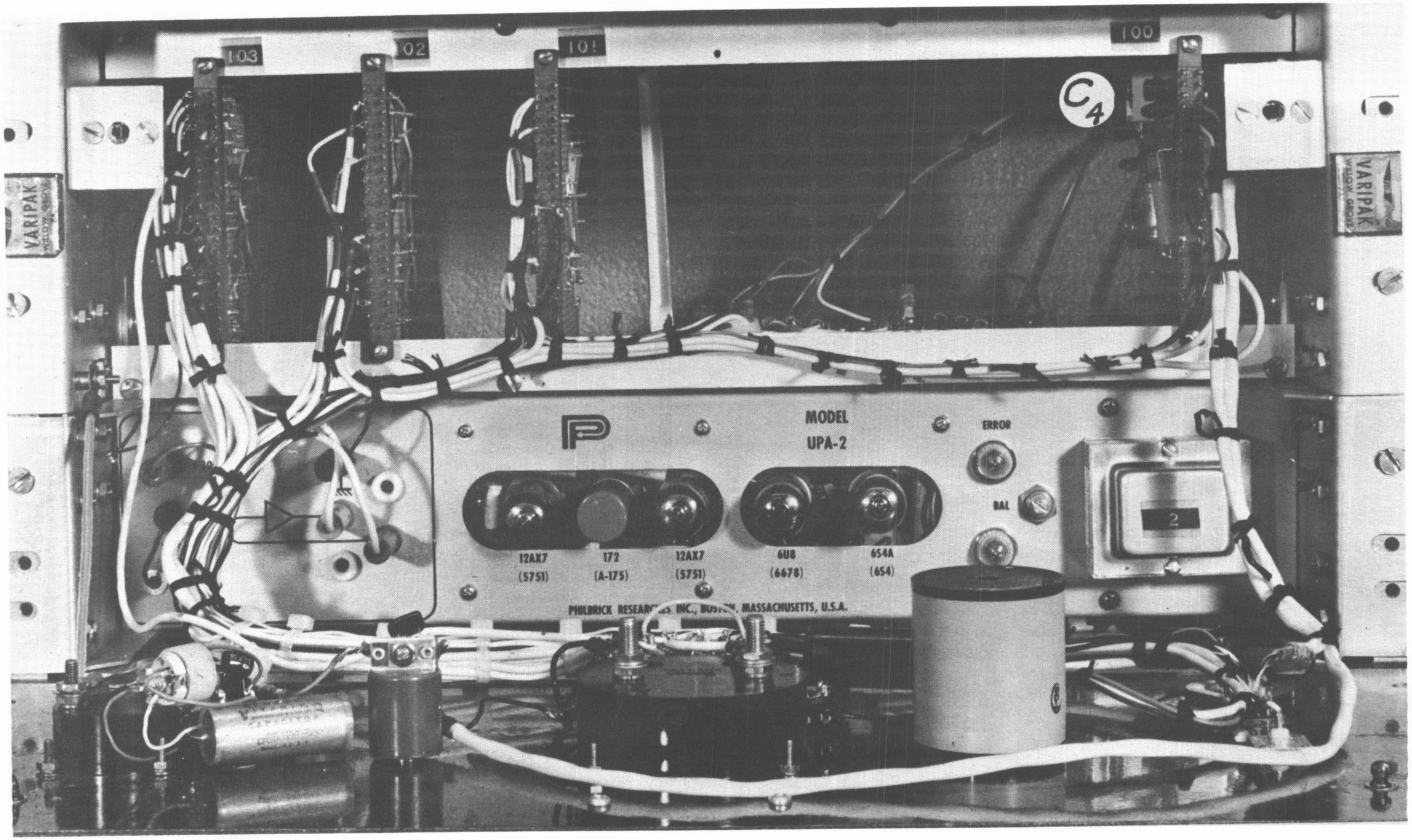

Figure 10. Servo Module Layout

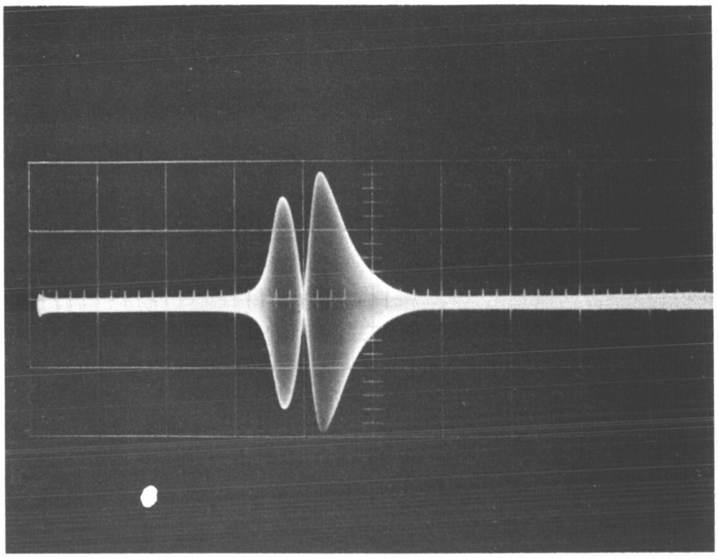

Figure 11. AC Signal Output Versus Laser Frequency

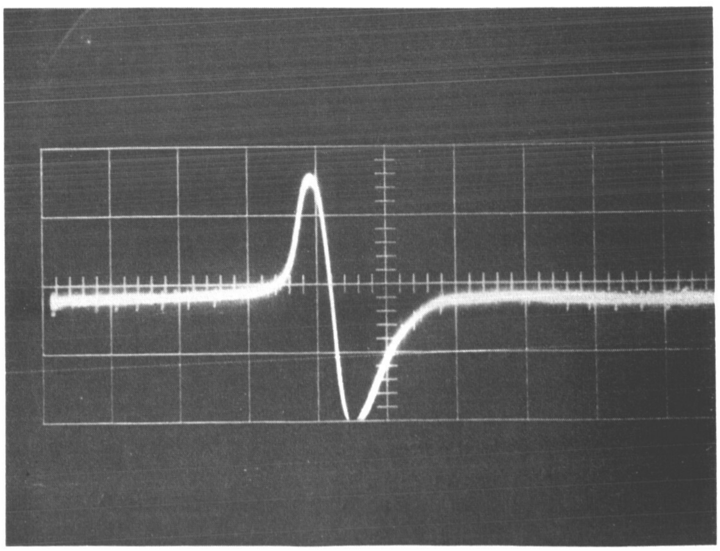

Figure 12. Discriminant Output

APPENDIX B

LASER WAVELENGTH STABILIZATION WITH A PASSIVE INTERFEROMETER

by

Morley S. Lipsett and Paul H. Lee

Reprinted from **APPLIED OPTICS**, Vol. 5, page 823, May 1966

Laser Wavelength Stabilization with a Passive Interferometer

Morley S. Lipsett and Paul H. Lee

A control system has been devised for stabilizing the output wavelength of a laser by reference to an external passive optical element. This element, consisting of two spherical mirrors, forms an off-axis resonator that, when broadly illuminated by a laser beam, functions as a wavelength-sensitive discriminator. The stabilization control loop is closed by using a signal from this discriminator to tune the laser by moving one of its mirrors with a piezoelectric transducer. The error signal is proportional to changes in wavelength of the incident laser beam and is derived from the discriminator without deliberate frequency or amplitude modulation of the laser The optical arrangement does not return any light in the direction of the source and thus avoids wavelength pulling due to spurious reflections. Two independent helium–neon lasers operating at 6328 Å were stabilized against a common reference interferometer using this system. Their relative stability was studied by heterodyning the two outputs and analyzing the beat spectrum. Each feedback loop had a gain of 60 dB at dc falling off to 46 dB at 200 c/s and to 20 dB at 2 kc/sec. The resulting wavelength stability was about $\Delta\lambda/\lambda = 2 \times 10^{-10}$. The residual instability was mainly owing to room noise occurring at frequencies above the response of the feedback loops.

This paper describes a method to improve the wavelength stability of lasers using an optical analog of microwave-oscillator stabilization techniques.[1,2] The authors employ an interferometer that consists of two spherical mirrors as a stable and resonant optical pathlength reference external to the laser. The interferometer is completely passive and can be designed for high Q, for intrinsic stability, and for isolation from thermal and acoustical disturbances.

Our stabilization technique takes advantage of what happens when spherical-mirror interferometers of a special class are over-illuminated off axis. An interlaced mode pattern is set up evidenced by two bright spots on one of the mirrors and two bright lines on the other as shown in Fig. 1. When the wavelength of the incident illumination changes by an amount $\Delta\lambda$, the spots remain stationary but the lines move apart or together depending on the sign of the change, and the angle of the transmitted beam becomes an extremely sensitive function of wavelength. This effect is the basis for an optical discriminator built as shown in Fig. 2 using a beam-dividing prism, two photomultipliers, and a differential amplifier. From changes in angular position of the transmitted beam, an analog electrical signal is obtained proportional to $\Delta\lambda/\lambda$. This signal is amplified and applied to a piezoelectric transducer to control the mirror spacing of the laser source. When adequate loop gain is provided, the length of the laser is stabilized against the interferometer reference.

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Received 22 December 1965.

As shown in Fig. 3, the interferometer comprises two identical spherical mirrors, M_1 and M_2, at a near confocal spacing of $R + \epsilon$, where R is the radius of curvature of the mirrors and ϵ is a small additional separation (in practice, negative). A laser beam is focused to a point P_2 on M_2. It is incident off axis on M_1, and there it illuminates a patch of diameter, d. An incident ray enters the interferometer at a point, P_1, and undergoes reflection at points P_2, P_3, and P_4 before returning to a point, P_5, near P_1. The optical path length between P_1 and P_2 is l_1, and the subsequent path lengths are likewise denoted l_2, l_3, and l_4, respectively. An axis is formed by a line connecting the two centers of curvature. We define $Y_{1,2\ldots5}$ as the normal distances of the respective points $P_{1,2\ldots5}$ from this axis. The observed mode distribution requires that (a) P_5 coincide with P_1, (b) the axis be a line of symmetry, and (c) the total optical path be an integral number of wavelengths, N, of the incident beam. Therefore,

$$Y_1 = Y_5 = Y_3$$

$$Y_2 = Y_4$$

$$l_1 + l_2 = l_3 + l_4$$

$$2(l_1 + l_2) = N\lambda, \tag{1}$$

where N is of order $4R/\lambda$.

When these relations are combined and expressed exactly in terms of R and ϵ, one obtains $N\lambda = 2$ [(F −

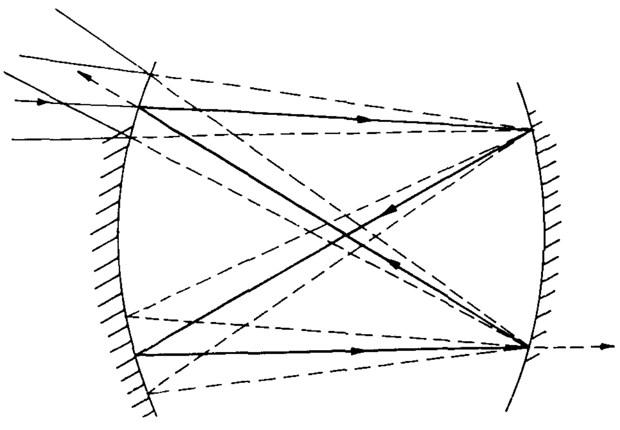

Fig. 1. Illustration of interlaced mode pattern used for the stabilization technique.

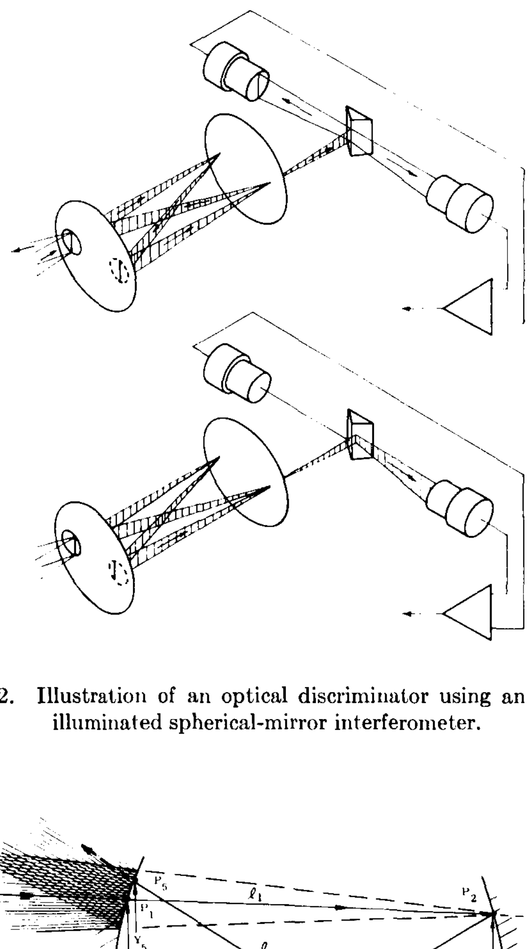

Fig. 2. Illustration of an optical discriminator using an over-illuminated spherical-mirror interferometer.

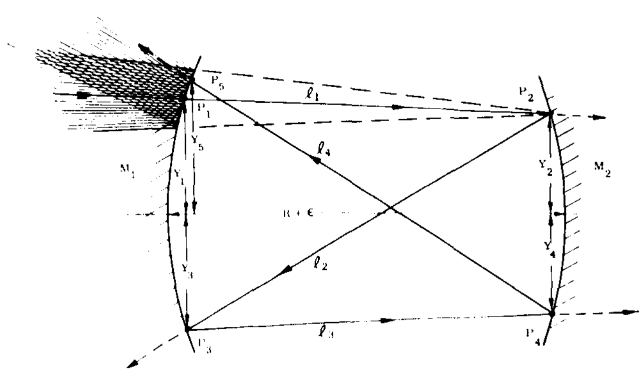

Fig. 3. Interferometer ray diagram.

$2Y_1Y_2)^{1/2} + (F + 2Y_1Y_2)^{1/2}]$, where

$$F = 3R^2 + \epsilon^2 - 2\epsilon R + 2(\epsilon R - R^2)(\alpha^{1/2} + \beta^{1/2}) + 2R^2(\alpha\beta^{1/2}) \quad (2)$$

$$\alpha = 1 - (Y_1/R)^2, \text{ and } \beta = 1 - (Y_2/R)^2.$$

A further condition is imposed by the reflection angles at the mirrors and constrains the values of ϵ. The resonator parameters that we used justified the following approximation:

$$\Delta Y_1/Y_1 \sim -2R^4(Y_1^2Y_2^2 + 2\epsilon RY_1^2)^{-1}\,\Delta\lambda/\lambda \sim 10^8\,\Delta\lambda/\lambda. \quad (3)$$

Note from Figs. 1, 2, and 3 that this resonator has the characteristic property of a circulator and does not return any of the incident light beam on itself. In this way, the laser is isolated from the interferometer, and problems of optical feedback are avoided.

Two independent lasers were slaved to a common passive interferometer of the type described. The arrangement used is illustrated schematically in Fig. 4; a photograph of the actual setup is shown in Fig. 5. The laser plasma tubes are mounted with the Brewster angle windows facing horizontally in one case and vertically in the other. As a result, the output beams have perpendicular planes of polarization. These beams are made collinear with a mirror and a beam splitter. Half of this superposed light is used to illuminate the interferometer. The other half passes through a Polaroid filter oriented at 45° to both planes of polarization and, on detection by a photodetector, is used to monitor the spectrum of beats between the lasers.[3,4]

The back surface of each interferometer mirror is curved to function as a positive lens which focuses an incident parallel beam on the far mirror.

Transmitted light is separated by a calcite prism, and the constituent beams lead to separate beam-dividing prism, photomultipliers, and differential amplifiers, as shown in Fig. 4. The two resulting error signals are amplified by a pair of high-voltage operational amplifiers and drive the transducers that tune each laser, respectively. In this way, both lasers are stabilized with negligible interaction in closed-loop fashion against exactly the same path length in the interferometer. This establishes an identical mean wavelength for both lasers and, therefore, a beat spectrum centered at dc. However, one laser can be offset slightly with respect to the other by a lateral adjustment of one of the beam-dividing prisms. This allows the beat spectrum to be shifted up in frequency to where a low-frequency panoramic spectrum analyzer can be used conveniently.

The lasers used for this work furnish several hundred microwatts in a single mode at 6328 Å and consist of dc-excited He–Ne plasma tubes and external mirrors arranged as shown in Fig. 4.

Each laser was tuned by changing the spacing of its mirrors with a piezoelectric transducer. The transducers consisted of stacked PZT-5 (Clevite) wafers used in the thickness-expander mode, and tuned the lasers by an amount $\Delta\lambda \sim 10^{-4}$ Å ($\Delta\nu \sim 10$ Mc/sec) per applied volt.

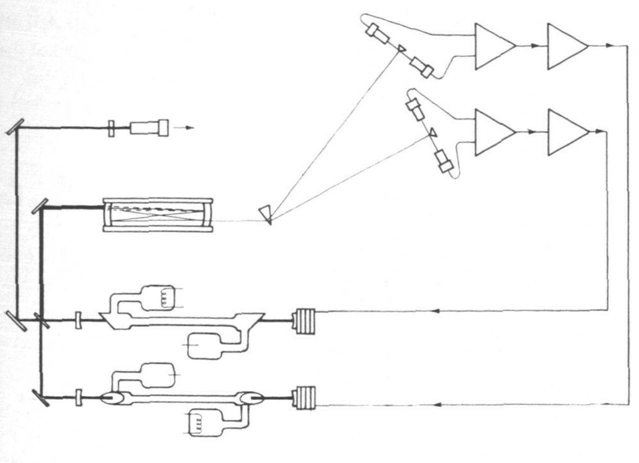

Fig. 4. Schematic diagram showing two independent lasers slaved to a common passive interferometer.

Fig. 5. Photograph of experimental equipment corresponding to Fig. 4.

The reference interferometer mirrors were held by an open Invar frame. At slightly less than the confocal spacing of 10 cm, they supported the requisite mode pattern. The interferometer was adjusted to be resonant over a frequency range of about 24 Mc/sec with a nominally plane incident beam of 1.5 mm diam. The values of Y_1 and Y_2 were 1.5 mm (at the center of the incident beam) and 0.5 mm, respectively, and ϵ was estimated from Eq. (3) to be about -0.1 mm.

An error signal was derived from each beam-dividing prism with two EMI 9592 B photomultiplier tubes and a modified Tectronix Type D differential amplifier. When the transducers were driven open loop with a sawtooth voltage, these signals took the shape of a familiar discriminator curve. An oscilloscope photograph is reproduced in Fig. 6 to illustrate this behavior. The bottom trace is the voltage applied to one of the transducers (vertical sensitivity = 10 V/division). The upper trace is the output from the respective differential amplifier (5 V/division). Measured in terms of the laser frequency changes represented by the lower trace, the slope of the steep part of the discriminator curve is approximately 1 V $(\mathrm{Mc/sec})^{-1}$. The peak-to-peak range of the discriminator is about 24 Mc/sec.

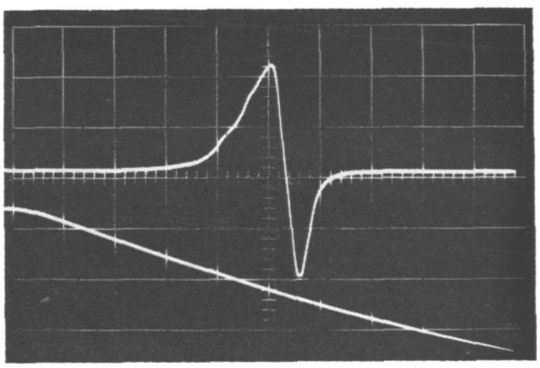

Fig. 6. Oscilloscope photograph of discriminator characteristics. The upper trace shows the output of one of the discriminators for a linear change in wavelength of the incident laser beam (produced by applying a ramp signal, shown in the lower trace, to the laser transducer). The slope of the central part of the discriminator curve is about 1 V/(Mc/sec).

The stabilization loops were closed with modified KEPCO ABC 1500 M power supplies which acted as high-voltage operational amplifiers and which brought the net gain of each loop up to about 60 dB at dc. It was found that troublesome phase shifts occurred in the loops beyond a few kilocycles per second owing to mechanical resonances in the transducer assemblies. For this reason, break points were introduced at the inputs to the transducers which cut the loop gain by 14 dB at 200 c/s and 40 dB at 2 kc/sec. As a result, the loops were closed only between dc and relatively low audio frequencies.

When closing the loops one could watch the system drift into lock, at which time the interlaced mode pattern in the interferometer was clearly visible. Then the lasers would behave as sensitive microphones. One could literally whisper to the lasers and observe voice modulations on the error signals caused by the induced frequency fluctuations.

A typical record of the beat spectrum as displayed by a low-frequency panoramic spectrum analyzer is shown in Fig. 7. The width at half-maximum was on the order of 100 kc/sec. Some of this width was because of electrical noise in the loops, but most was caused by high-frequency sound outside the bandwidth of the

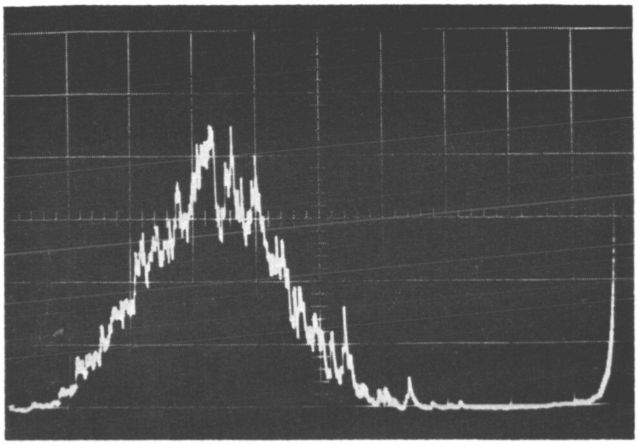

Fig. 7. Photograph of beat spectrum. Horizontal scale (from right to left) 0–500 kc/sec (peak at right is due to analyzer imbalance at dc); sweep time 0.5 sec; linear vertical scale.

feedback loops. This was seen by examining the feedback error signals, which were found to contain frequency components mostly between dc and 10 kc/sec. The spectrum of the error signals correlated well with voice and other sources of sound in the room. On the other hand, the effect of sound below about 200 c/s was observed to be strongly degenerated by the loop gains around the lasers.

From knowledge of the beat spectrum we can infer that the relative wavelength stability of the lasers was about $\Delta\lambda/\lambda = 2 \times 10^{-10}$.

The authors cannot infer similarly the absolute stability of the lasers in this instance since the interferometer was not protected from ambient temperature changes. It is interesting to note, however, that the interferometer was open to the atmosphere and acted as a true wavelength-in-air reference. As a result, the lasers were tuned to a constant wavelength irrespective of barometric pressure variations. The range of compensation for pressure variation using this kind of arrangement is limited, in general, by the tuning range of the laser.

The authors are grateful to G. W. Stroke who contributed to an early phase of this work, to C. E. Theall for his important share in the electronic design and construction, and to D. B. Harris who carried out a detailed analysis (not yet published) of the over-illuminated-mode behavior. The authors have had the benefit of many helpful discussions with J. G. Atwood and wish to acknowledge his encouragement and direction of the work reported in this paper.

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3. A. Javan, E. A. Ballik, and W. L. Bond, J. Opt. Soc. Am. **52**, 96 (1962).
4. M. S. Lipsett and L. Mandel, Appl. Opt. **3**, 643 (1964).

APPENDIX C

RETRACING RAYS IN A NEAR CONFOCAL RESONATOR

by

Duncan B. Harris

RETRACING RAYS IN A NEAR CONFOCAL RESONATOR

Duncan B. Harris
Perkin-Elmer Corp.

This work is an extension of the analysis carried out in a paper of Morley S. Lipsett and Paul H. Lee[1].

The problem considered is that of two spherical mirrors of equal radius R, placed at a nearly confocal configuration (see fig. 1). A cone of laser light enters at one mirror and is focused to a point at the surface of the other mirror. Under proper conditions, a small bright spot appears on the entering mirror, within the original cone. The position of this spot (and one at a point symmetric about the center of the mirror) depends on the wavelength of the laser light. The relationship between the spot position and the laser wavelength is investigated.

Since the vertex of the incoming cone of light does not move, the change in spot position can be translated into a change in angle. The resonant ray can be made to fall on a prism which splits it into two parts, each of which is measured by a photomultiplier (see fig. 1). Lipsett and Lee[1] put the output from the photomultipliers through a differential amplifier and a piezoelectric transducer which controlled the mirror spacing of the laser itself. In this way, the confocal resonator acted as an optical discriminator whose output was used to stabilize the wavelength of the laser source.

[1]Lipsett, M.S. and Lee, P.H. "Laser Wavelength Stabilization with a Passive Interferometer"

In order to carry out the analysis, we make some simplifying assumptions. We shall consider the cone of light to be a bundle of rays, and shall assume that the central ray is in the same plane as the axis of the resonator system. We then consider only this plane. The ray picture gives a simple explanation for the bright spots when the rays retrace themselves. We therefore look for situations where the rays retrace themselves, or nearly so.

In general, we have the case shown in Fig. 2. A single ray lists points $Y_1 \ldots Y_5$, which are the successive heights of the reflected ray. Assuming that the ray retrace itself implies:

$$Y_1 = Y_3 = Y_5$$
$$Y_2 = Y_4 \qquad (1)$$

These conditions yield a path length:

$$L = 2\ [(A + D)^{1/2} + (A - D)^{1/2}]$$

where

$$A = 3R^2 + E^2 - 2ER + 2R\ (E-R)\ (B+C) + 2R^2BC$$
$$D = 2\ Y_1\ Y_2$$

where in turn E is the axial displacement of the mirrors minus their radius of curvature and

$$B + (1-Y_1^{\ 2}/R^2)^{1/2}$$
$$C + (1-Y_2^{\ 2}/R^2)^{1/2} \qquad (2)$$

For resonance, there must be an integer N such that:

$N\lambda = L$ (3) (λ - wavelength of incoming light)

These equations determine $N\lambda$ from Y_1, Y_2, R, E. However, satisfying equations (1) does not, in general mean satisfying the law of reflections. Fig. 3 indicates that for a given parallel ray and a given radius R, there is some mirror displacement, hence an E, for which that ray retraces itself. To calculate the relationships, fig. 3 yields:

$$\sin a = Y/R$$

$$\cos b = X\,(4Y^2 + X^2)^{-1/2}$$

$$\sin b/2 = \left((1-\cos b)/2 \right)^{1/2} \qquad (4)$$

The requirement that $\sin a = \sin \frac{b}{2}$ determines X.

Then $E = R + X - 2\,(R^2 - Y^2)^{1/2}$ (5)

The results, shown in fig. 4 indicate that E must be negative (mirrors closer than confocal) and that E varies approximately with the square of Y. Denote the E which causes a parallel ray at height Y to retrace by E_Y. Since there are no other "obvious" rays which retrace themselves exactly, we choose our central ray parallel to the axis at Y. Call this ray r_Y. Then for rays close to r_Y and E close to E_Y, we have rays nearly retracing themselves. To give an estimate of how close a ray actually comes to retracing, we define a spot radius to be half the length of the cord whose (maximum) distance from the mirror surface is $\lambda/4$ (see fig. 5).

Spot radius $= r_s = 1/2\ (2\lambda R - \lambda^2)^{1/2}$ (6)

For λ= 6328A, r_s was of the order .17 m.m. This is in good agreement with the mode size for a confocal cavity as defined by Boyd & Gordon[2].

[2] Boyd, G.D. and Gordon, J.P. "Confocal Multimode Resonator for Millimeter thru Optical Wavelength Masers, Bell System Journal, Mar. 1961, page 497.

A computer program was written which for a given R,E and initial Y_1, Y_2, gave values of λ, and Y_2 on each successive bounce, and determined how many total passes (4 bounces for each pass) the given ray made before one of the values of Y_1 or Y_2 was one spot radius away from the initial values. Fig. 6 shows the results of these computations for various values of the parameter. Note that the width of the peak decreases with increasing $|E|$ (Center of cone farther off axis). This suggests taking the center ray fairly close to the axis (but not far enough away to avoid overlapping spots).

Thus equation (2) is reasonably valid for near parallel rays for the proper E. Therefore we calculate $^{d\theta}/d\lambda$ exactly, and also using the approximations:

$$E/R,\ Y_1{}^2/R^2,\ Y_2{}^2/R^2 << 1$$

$$^{d\theta}/d\lambda = N / \left[(A-D)^{-1/2} \left(-2Y_2-2(E-R)Y_1 /BR - 2Y_1\, C_{/B}\right) + (A+D)^{-1/2} \left(2Y_2 - 2Y_1 (E-R) /BR - 2Y_1\, C_{/B}\right) \right] \quad (7)$$

(symbols as before)

and

$$^{d\theta}/d\lambda \text{ (approx)} = 2R^3 \left(y_1\, y_2{}^2 + 2E\, R\, Y_1\right)^{-1} /\lambda \qquad (8)$$

For λ near 6328A and parallel rays r_Y, E was varied near E_Y.

$^{d\lambda}/d\theta$ (exact) vs. E is shown in fig. 7. For E= E_Y $^{d\lambda}/d\theta = 0$,

i.e. $^{d\theta}/d\lambda = \infty$. Therefore we wish to choose E fairly near E_Y, but not too close in order to have both retracing rays and good resolution. Also note that the slope of $^{d\lambda}/d\theta$ vs E increases with increasing Y. Thus working close to the axis enables one to have a large ${}^{d\lambda}/d\theta$ with E nearer E_y.

${}^{d\theta}/d\lambda$ gives a measure of the sensitivity of the optical discriminator. Therefore we want ${}^{d\theta}/d\lambda$ to have a suitable magnitude. ${}^{d\theta}/d\lambda=0$ means no change in angle for a shift in wavelength, and ${}^{d\theta}/d\lambda=\infty$ means no change in wavelength for a given angular change. For a central ray at height y_1 fig. 6 gives the maximum shift in Y_1 that will give a specified number of passes through the resonator. λ must be (externally) held to about 1 part in 7×10^5 (the value of N in eq. 7), since if λ changes by more than this amount, N will change, and the discriminator will attempt to stabilize at a new λ. Actual best values for ${}^{d\theta}/d\lambda$ will depend upon how accurately it is possible to build a resonator with a particular E, since E determines the central ray r_y (fig 4) and thus the maximum allowable shift in Y_1.

Many thanks are due to J. G. Atwood, Dr. J. D. Rigden, P. H. Lee, and M. S. Lipsett whose ideas led directly to the work described herein. Also helpful was the experimental demonstration by V. W. Luban.

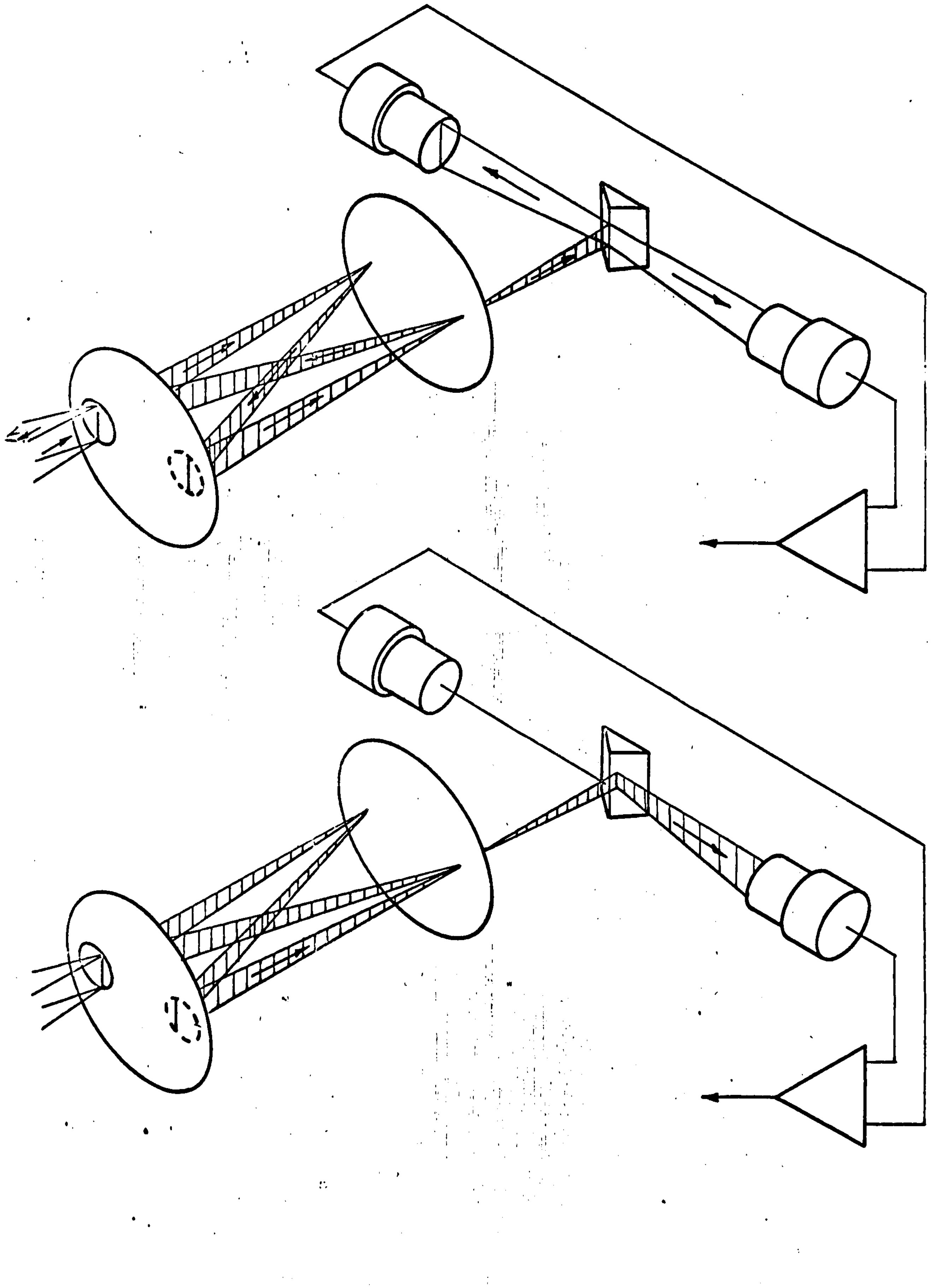


Fig 1 Courtesy Lipsett + Lee

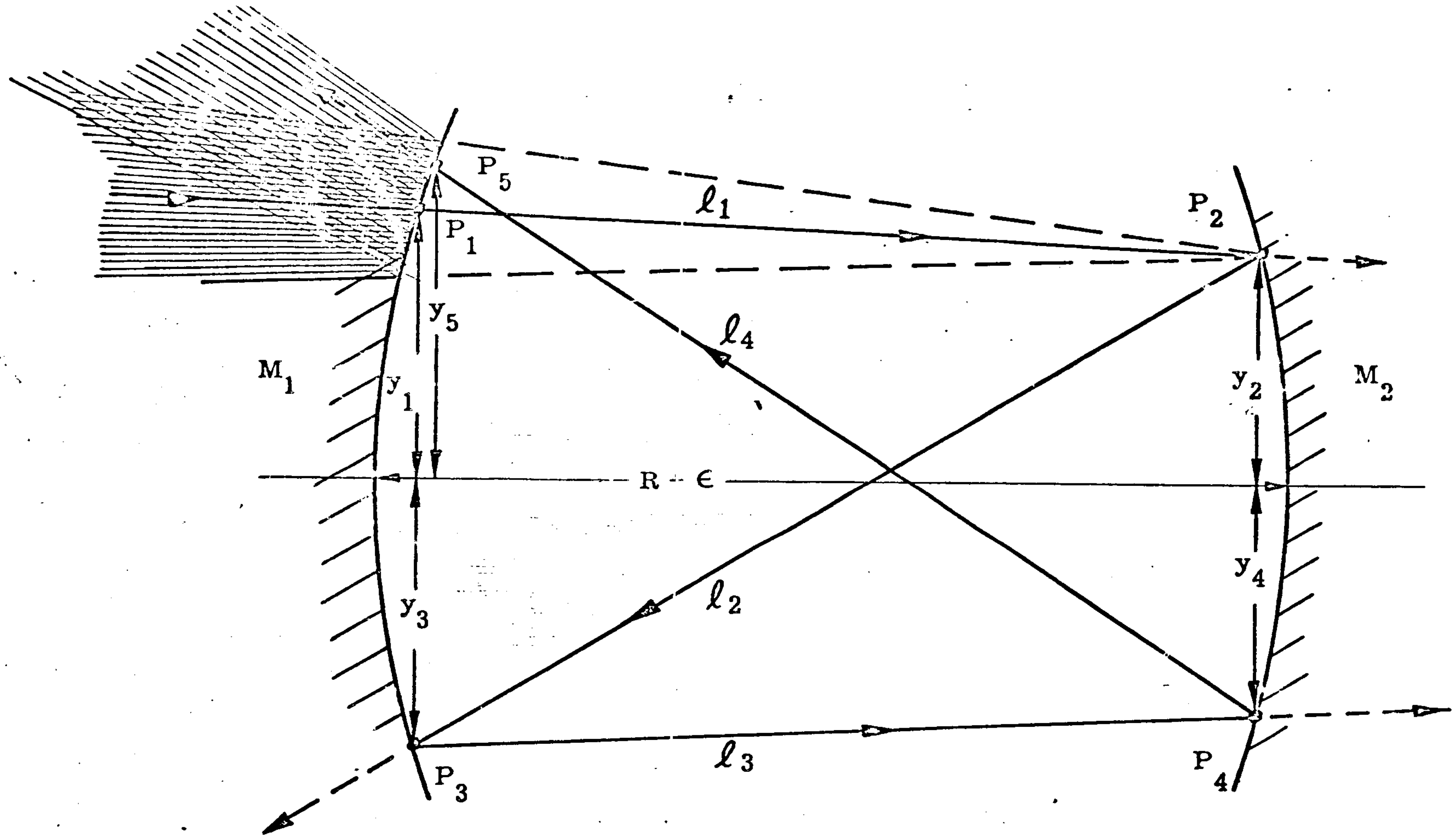


Figure 2.

Courtesy Lipsett + Lee

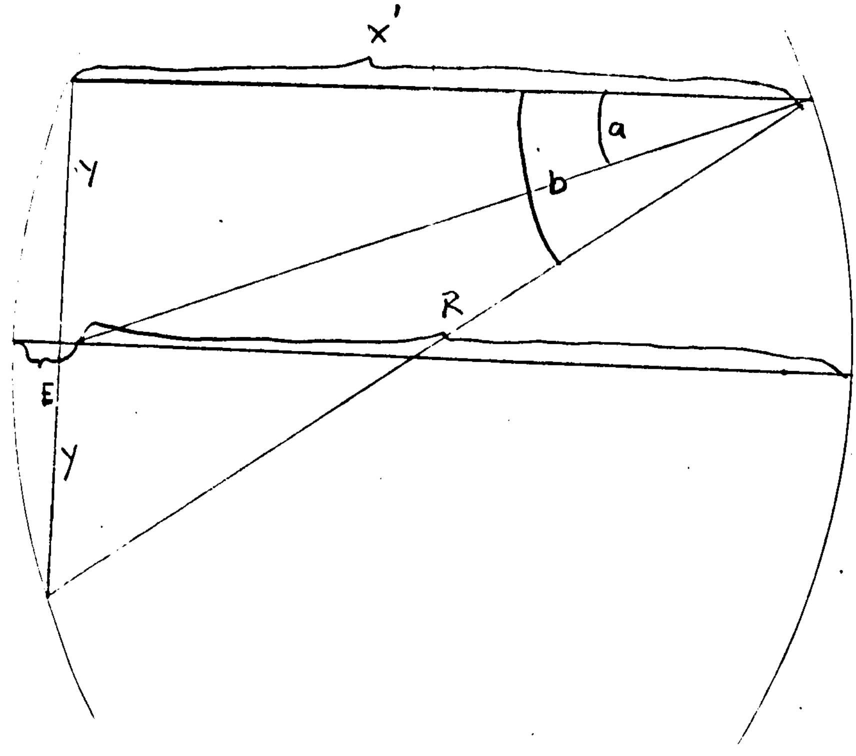


Fig 3

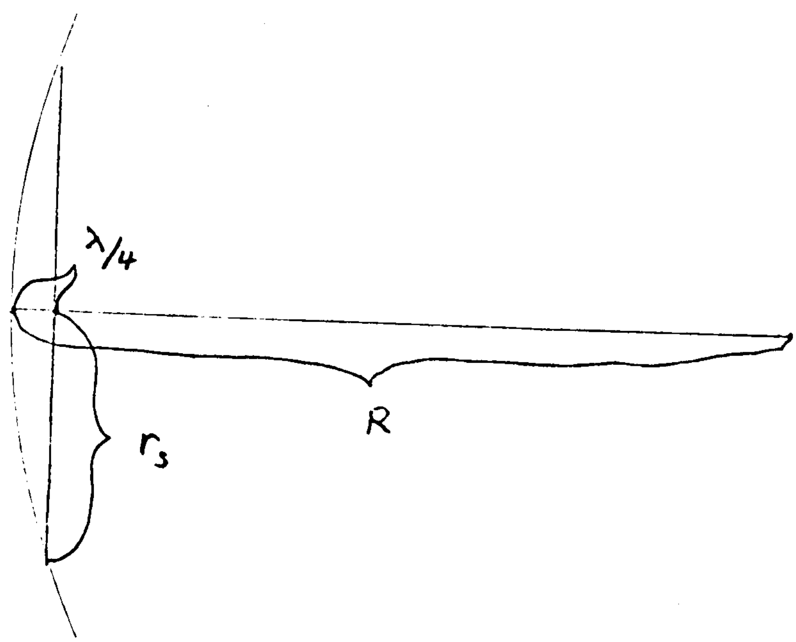


Fig 5

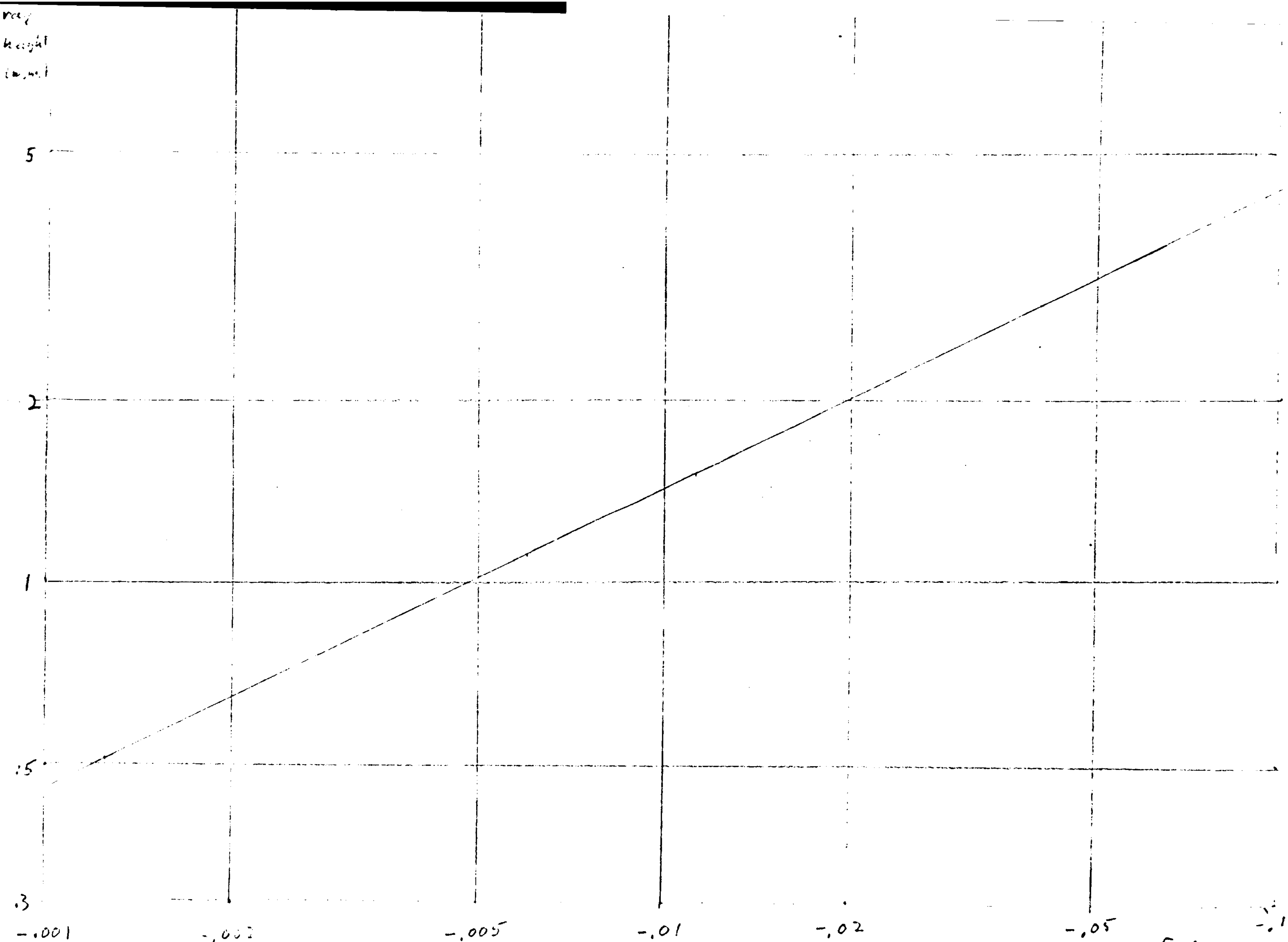
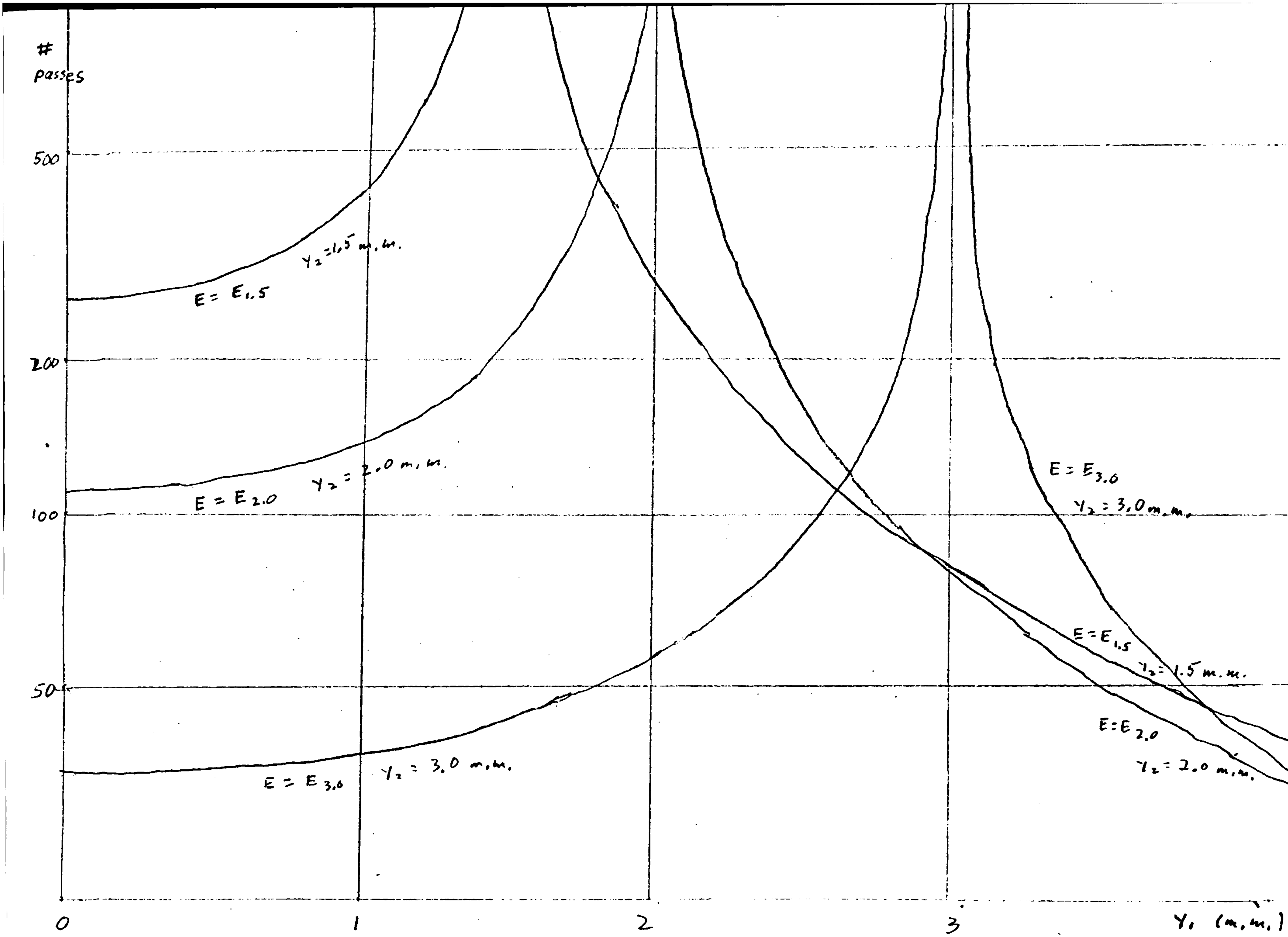


Fig 4 Plot of ray height (y) vs E (units are mm)



Plot of # passes vs Y

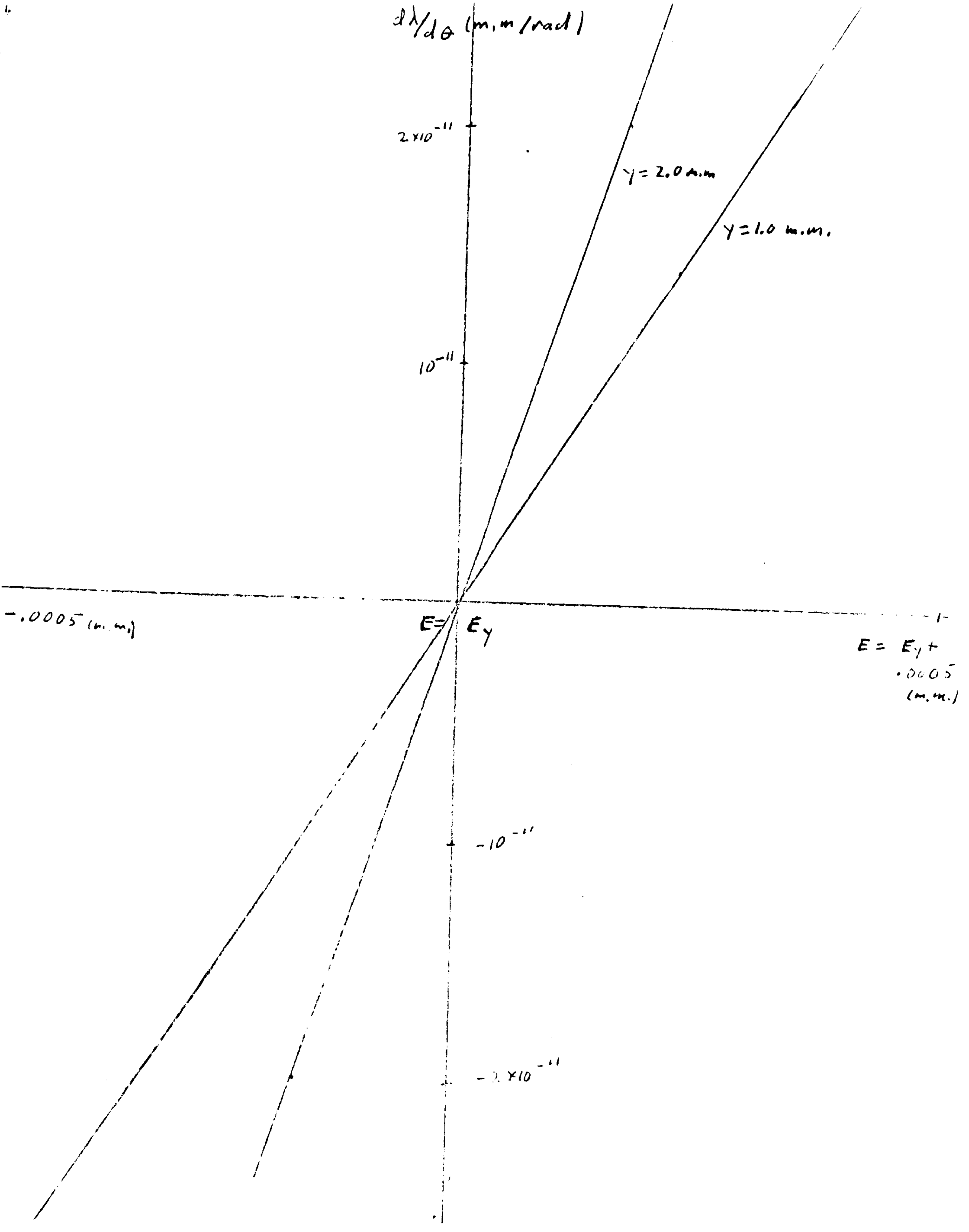


Fig 7
Plot of $d\lambda/d\theta$ vs E for parallel rays at 1.0 and 2.0 m.m
(E scale centered on $E_{1.0}$ and $E_{2.0}$ respectively)

APPENDIX D

A PHASE COMPARISON OPTICAL DISCRIMINATOR

by

Paul H. Lee and Michael L. Skolnick

A Phase Comparison Optical Discriminator

Paul H. Lee and Michael L. Skolnick

The Perkin-Elmer Corporation, Norwalk, Connecticut

The frequency of a laser oscillator may be stabilized by slaving it to the resonance of a passive reference cavity.[1] This letter describes a new method for generating the error signal needed to control the laser frequency. The technique employed is an optical analog of the A-C Pound Stabilizer often used to improve the frequency stability of tunable microwave sources.[2,3]

The technique devised does not modulate the laser frequency. The output light will therefore be useful for narrow bandwidth applications. It also does not modulate the length of the reference cavity. This cavity can therefore be built to take full advantage of the most stable materials and structures.

Figure 1 shows the transmission and the optical phase shift as a function of frequency of the light passing through a resonant cavity. Because the transmission function is symmetric about the resonance, its direct use as a frequency discriminant is complicated by sign ambuigity. The optical phase shift function however, is not symmetric about the resonance center. It can be used to generate an unambiguous error signal when compared with reference light of the proper phase and amplitude. We have built an optical discriminator which converts this phase shift information to a frequency error signal. The apparatus and results are described below.

A two arm (Mach-Zehnder) interferometer was used as the necessary phase measuring bridge. A diagram of the apparatus is shown in Figure 2.

Following the first beam splitter, one arm of the interferometer contained the passive reference cavity. The other provided the reference light and in addition contained an optical phase modulator to be driven by the reference signal from a synchronous detector. The beams from both arms of the interferometer were recombined at the second beam splitter. The recombined beam was detected by the photomultiplier which in turn furnished the input signal for the synchronous detector as shown.

The bridge was initially balanced in transmission and phase so that when the laser was manually tuned to the center of the cavity resonance the beams from both arms interfered destructively. When the laser frequency was then detuned from the center of the cavity resonance, the phase of the light from the arm containing the cavity changed rapidly. The resulting intensity change in the bridge output was proportional to the change in laser frequency. The optical phase modulator was then turned on and resulted in a sinusoidal intensity modulation of the bridge output beam proportional to the laser detuning from the cavity resonance. The phase of this modulation with respect to the modulator drive signal reversed with the sign reversal of the laser detuning. This phase and intensity information was converted by the synchronous detector to be the final electrical discriminator output signal.

The interferometer was illuminated by a 150 μwatt single mode, He-Ne laser (λ = 6328Å). One arm of the interferometer contained a 10cm long reference cavity with a fused silica spacer. The other arm contained a resonantly driven (100 kHz) optical phase modulator. The output frequency of the laser was swept across the cavity resonance by a sawtooth voltage applied to a piezoelectric transducer moving the laser mirror.

The resulting output signal from the synchronous detector is shown in the upper trace of Figure 3 as a function of laser frequency. The lower trace shows the simultaneous transmitted intensity. The horizontal scale of the photograph is 60 mHz per division. The 100 kHz carrier has not been filtered out. The upper trace of the photograph shows the desired discriminator shape as the laser frequency passes through the cavity resonance.

An additional advantage of the system described is that it operates with a dark fringe at the photodetector. This results in reduced shot noise in the detector and permits use in servo systems with correspondingly higher gain bandwidth products.

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[2] Pound R. V., Rev. Sci. Instr. 17, 490 (1946)

[3] Pound, R. V., Proc. Inst. Radio Engineers, 35, 1405 (1947)

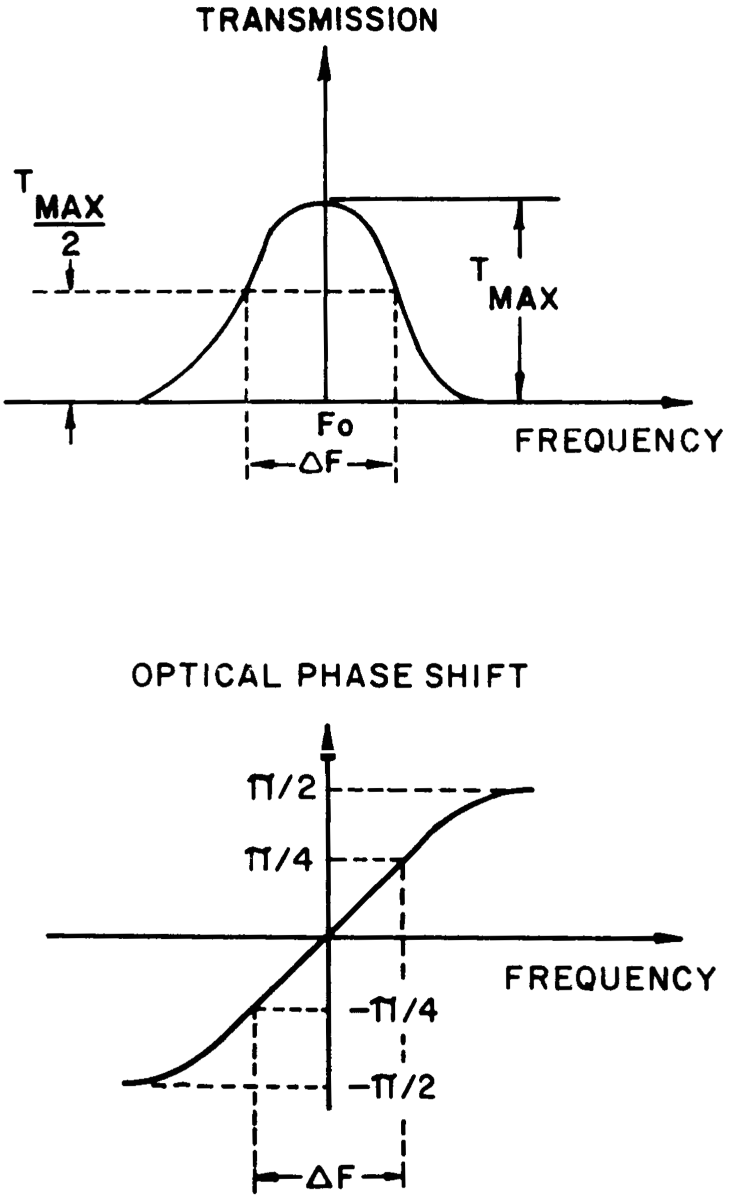

Fig. 1 - Transmission and Optical Phase Shift of A Passive Resonant Cavity. F_o is the Resonant Frequency. ΔF is the Linewidth at Half Transmission.

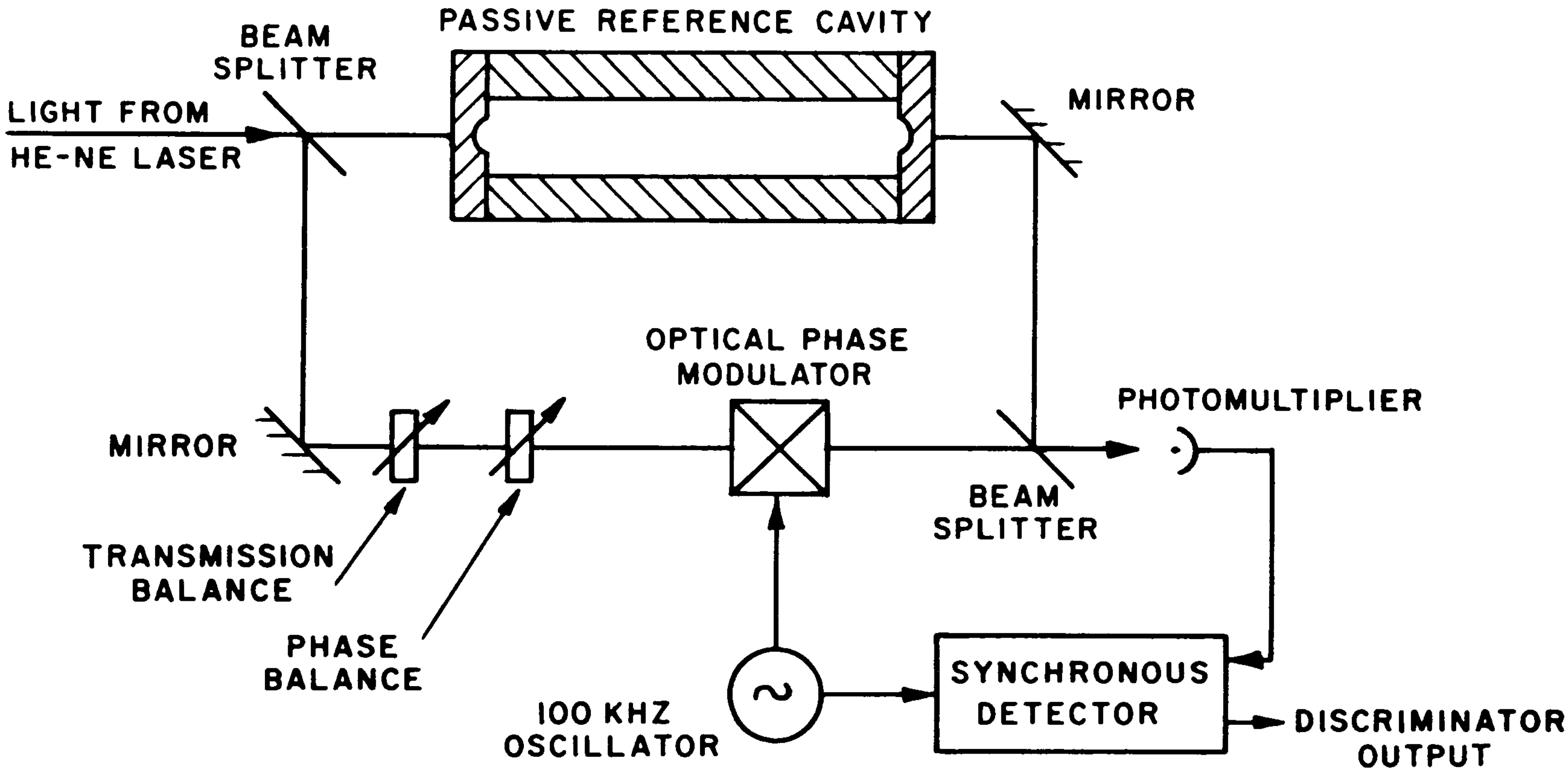

Fig. 2 - Optical Phase Sensing Discriminator.

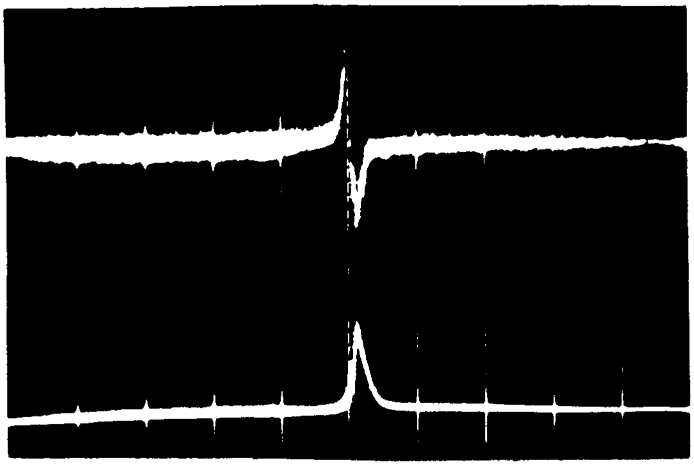

Fig. 3 - Discriminator Output and Transmitted Power As Functions of Frequency.